COMPUTER AIDED ASSEMBLY LINE BALANCING WITH PROBABILISTIC PARAMETERS

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By
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CERTIFICATE

Certified that this work on "Computer Aided Assembly Line Balancing with Probabilistic Parameters" by B.V.R. Mohan Reddy has been carried out under my supervision and that this has not been submitted elsewhere for a degree.

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SYNOPSIS

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COMPUTER AIDED ASSEMBLY LINE BALANCING WITH PROBABILISTIC PARAMETERS

(Analysis of data collected on assembly lines from some of the leading Indian industries indicate that there is a high variability associated with work element times and also there is a wide difference in the capabilities of the operators.) The present work attempts to account for such variabilities in balancing single model industrial assembly lines. Three methodologies have been developed to take care of these two variabilities on the assembly lines. They are :

(i) A modified rank positional weight technique for accounting the variability in work element times.

(ii) A biased sampling scheme to account for variabilities in work element times and

(iii) A procedure of loading stations maximally to jointly account for probabilistic work elements and variable operator performance level.

All the above three heuristic approaches are tested for four assembly line problems. The four problems are :

(i) The Assembling clothes problem.

(ii) The T.V. Main Chassis assembly problem.

(iii) The Refrigerator final assembly problem and

(iv) The Truck assembly problem.)

This research was carried out bearing in mind that a balance is to be maintained between obtaining an optimal solution and the cost of obtaining the optimal solution. A satisfactory solution is being sought at the expense of reseasonable computation time on the computer. The results show that the proposed methodologies provide a sound solution rapidly. The computational effort needed to solve large scale balancing problems does not increase appreciably from that of a small scale balancing problem. In addition the methodology provides a great deal of flexibility for management in the implementation of the solution.

CHAPTER 1

INTRODUCTION

The design of a production system involves decisions regarding the optimal planning and control of men, materials, money and processes. One of the most important decisions to be taken before a process is designed is the selection between job-shop and flow-shop types of production. Many tangible and intangible factors affect the selection. The cost of equipment, the percentage utilization of labour, the cost of learning, the fixed capital and working capital may be identified as some of the important tangible factors governing such a selection. Besides these factors, one needs to consider some of the intangible factors like employee's attitude towards the production process selected.

Flow-shop type production is commonly used in the assembly of parts, packing and shipment of finished goods, and the fabrication of component parts. Primarily flow-shop is used to manufacture goods in mass production. One of the most important application of concepts of flow-shop production is in the assembly of components. Assembly lines are widely employed in the manufacture of products which have in common a relatively heavy demand, fairly stable configurations and work content devisible into many components which can be performed one after another without delay. The products

commonly manufactured on assembly lines are automobiles, electronic gagets and home-appliances.

One of the important aspects of the assembly is the simplification of work into minute elements. This has been appreciated for generations, even before Adam Smith presented a paper on this subject in 1776 (31). A thorough search into the literature suggests that till 1913 there have been only a few isolated efforts to apply the principles in a scientific manner. In particular, the efforts by British Naval Dockyard for the assembly of pulley blocks is worth mentioning. However, the credit of introducing the first progressive assembly goes to Henry Ford. Henry Ford in 1913 introduced in his High-land Park plant the principles of division of work, interchangeable parts and movement of product past fixed work station with the basic idea of one man, one job or group of jobs.

The advantages inherent in assembly lines which result in a reduction in the product cost may be summed up as follows.

1. Assembly operations involve short and repetetive cycles which tend to increase productivity up to a point. The learning time is reduced and relatively less skilled labour can be employed.
2. Assembly components are fed at each work station. The control becomes easier due to the fact that each

operator is handling fewer components.

3. Higher production rates are possible because time consumed in obtaining parts is reduced.

4. Movement of assembly is usually with a conveyor which is one of the cheapest methods of material handling.

The disadvantages of using assembly lines are :

1. The control of quality becomes a difficult task due to continuous production.

2. The morale of the workers is affected as they are to function under paced conditions.

In an seembly line, facilities like machines, tools and manual operations are arranged successively and the work moves from one work station to another work station without backtracking. The characteristics of assembly lines are the simplification of the work into minute elements, allotment of work to a number of stations and unidirectional movement of assembly even when a production facility is required more than once. The method of assigning the work elements to work stations so that all stations get an equal amount of work is called "Assembly Line Balancing" (ALB).

Since 1913, there have been improvements over and above Fords concepts. The improvements were in the form of synthetic time study to improve individual's performance, use of power and hand tools to aid the operator to carry his

work. However, no serious attempt was made for the development of scientific tools for assigning the work elements to the work stations in order to obtain an optimal or near optimal balance. Essentially a few trial and error methods were developed and used.

Since 1950 there has been an enormous increase in the use of assembly line production concepts to take care of industrial demands for interchangability and higher production rates. A census was conducted by the University of Chicago, U.S.A., on the ratio of assembly workers to other operators for the period 1950 - 60. The results based on twenty five industially advanced American States revealed an increase in assembly workers by fifty percent during this period as against only eleven percent in other workers - a magnificient 5 : 1 ratio. Though this study was carried out for U.S.A. only, one could say that similar trends exist in other countries due to the introduction of modern manufacturing concepts into the industries all over the world.

First analytical approach for handling assembly line balancing problem was reported by Salveson (28) in 1954. His comprehensive treatment of setting and defining the problem are extremely valuable. The generally accepted definition of assembly line balancing problem is attributed to Salveson. According to him the objective in an assembly line balancing is "to minimize the total amount of idle time or equivalently

to minimize the total number of workers for a given conveyor-belt speed" depending on production rate requirements, the conveyor speed is fixed by the management. The maximum time that can be assigned to any work station is called cycle time. The cycle time is a function of the desired rate of production.

Since 1954, a number of models (as many as twenty) have been proposed and published on assembly line balancing problem. The methods which have been developed are of two types (1) optimum seeking algorithms which consider and accept or reject feasible sequences of elements within a well-defined mathematical structure; and (2) heuristic-type algorithms which incorporate logical decision rules to reduce the combinatorial content of the problem, in order to reach an optimal or near optimal solution. The latter type sacrificies assurance of optimality for the economy in computations required to achieve an acceptable balance.

Most of the assembly lines are single product assembly lines. However, in certain cases, an assembly line is required to handle simultaneously more than one model of the same general product. In literature this is referred as mixed - model ALB problem. In essence, a mixed model ALB problem is a mixed-model sequencing problem. The mixed-model sequencing problem occurs in industries which desire to keep several models in production rather than produce batches of

each intermittently. In mixed model balancing the objective is to sequence the units down the line so as to obtain the optimum utilization of assembly line operators. Kilbridge and Wester (34) were the first to handle the mixed model ALB problem in 1962. Since then very little progress has been made in this field.

Most of the work referred in this area is based on the following assumptions :

a. work element times are deterministic and are known exactly,

b. the average work performance level (that is, the average rating) of all operators is the same.

However, for industrial assembly lines the above assumptions are not valid. There is ample evidence to point out that the performance times are probabilistic and operator performance level is variable. Data collected from leading Indian industries employing large assembly lines confirm that there is high variability associated with work element times and also there exists a wide difference in the average work performance level between operators.

The work element times are actually random variables approximated by a normal distribution. Variations in work element times considerably affect the operation of an assembly line. In fact, if an operator on the line does not finish

the task assigned to him in time, the operator after him has to stand idle till the job is released by this operator and then after receiving the job he is under pressure to work faster to gain back the lost time. If he does not, the problem is passed on to the next operator. Therefore, an optimal solution with an assumption of deterministic times does not guarantee optimal solutions to industrial assembly lines because of the inherent variance in work element times.

Similarly average performance rating of all the workers on a line may not be the same. Therefore, the work alloted to a station should match with the operator alloted to the work station. If not, operators with higher performance level will complete the work within the cycle time and stand idle while the operators with lower performance level will not be in a position to complete the work within cycle time. This creates problems similar to the ones in variable performance times.

Keeping in view that the solution methodologies based on deterministic work element times and equal operator performance levels do not yield practical solution for industrial assembly lines, an attempt is made in this thesis to develop methodologies relaxing these two assumptions.

CHAPTER 2

SURVEY OF RELATED WORK

A survey of the literature in the field of assembly line balancing reveals that the research reported in this area can be broadly classified into two main categories. The categories are :

i. Single Model Assembly Line Balancing

ii. Mixed Model Assembly Line Balancing

In single model assembly lines, the objective is to allot the work elements equally to all the operators on the line. In the case of mixed model assembly lines, the problem is to sequence the units down the line so as to obtain the optimum utilization of assembly line operators. During the past two decades a number of algorithms have been suggested for balancing single model assembly lines. Research in the field of mixed model balancing got started only in the past decade and has not made much head-way in solving practical problems. The various methodologies reported in literature for solving single and multi model assembly line balancing are discussed in the following sections.

2.1 Single Model Assembly Line Balancing

The single model assembly line balancing methods developed so far can be divided into the following two classes:

i. Analytical Methods

ii. Heuristic Methods

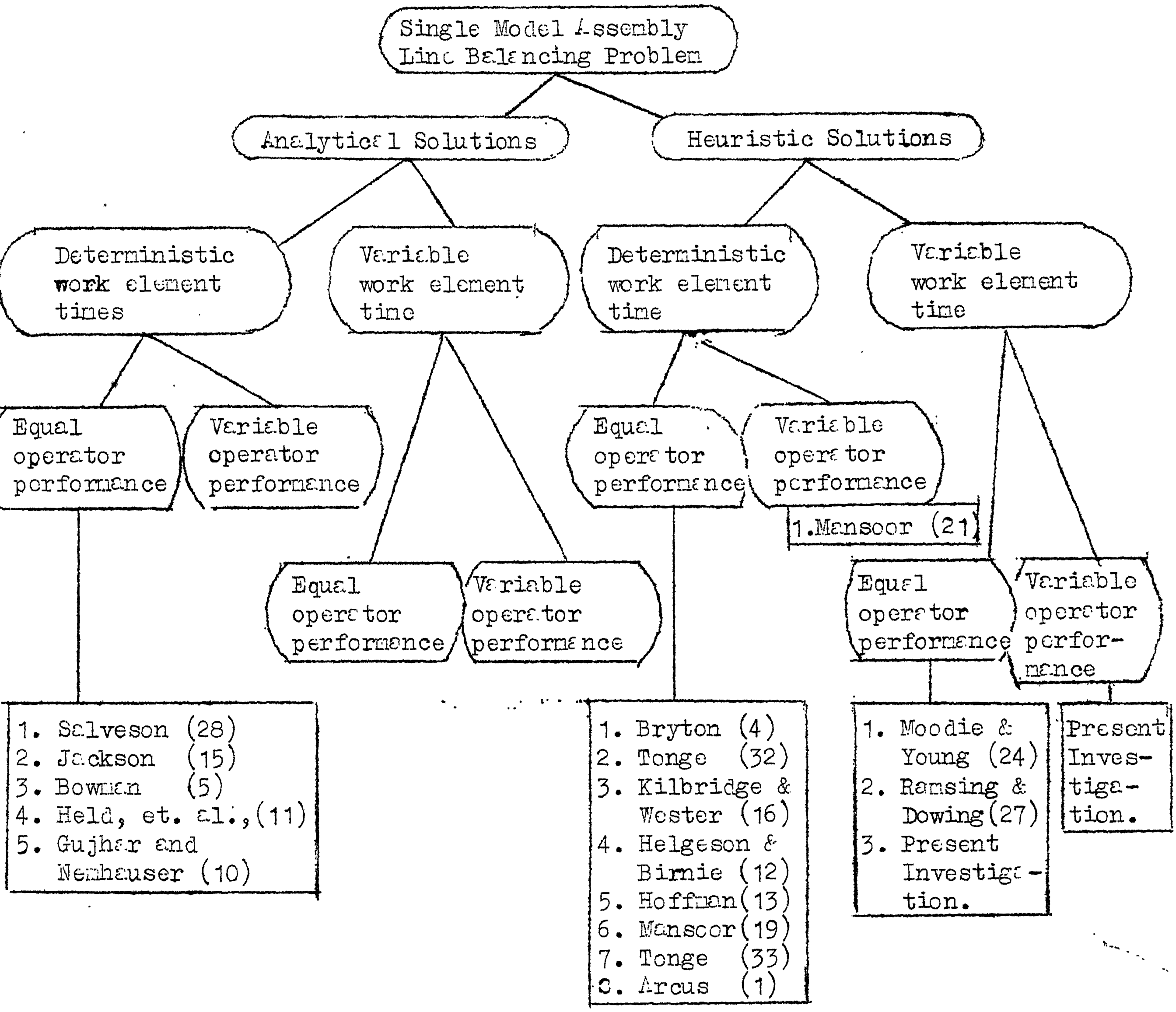


Fig. 2.1 DETAILS OF RESEARCH IN SINGLE MODEL ALB PROBLEMS

Figure 2.1 is a chart giving the details of the types of single model ALB problems which have been tackled so far by various researchers.

The first formal statement of the problem was made in 1954 by Bryton (4) in his unpublished master's thesis. Shortly thereafter Salveson (28) published an article on the formulation of line balancing problem. The discussion on line balancing literature is arranged in chronological order within each sub-section.

2.1.1 Analytical Methods

The first article published in this area was by Salveson in which he has described the line balancing problem. He uses the precedence diagram to represent ordering relations among work elements. Salveson points out that one could enumerate all possible work stations that best meet the requirements placed on the solution. He then goes on to propose a linear programming formulation of the problem. It should be noted that this linear programming formulation is incomplete and allows unacceptable sets of stations to be formed. His article contains many useful insights into the relation between the assembly line balancing problem as it exists in an industry and the abstraction necessary for the application of mathematical techniques. However, the computational techniques suggested by him are stated very vaguely and therefore, complete evaluation of their usefulness is impossible.

Jackson (15) has developed a computational procedure using exhaustive enumeration. The method consists of enumerating all possible first stations, and so on so forth. Rules are given for eliminating one of the two sequences of stations containing same elements and for eliminating that one of the otherwise identical stations containing smaller parallel elements. The author claims that the technique is exhaustive and therefore yields an optimal solution. The main drawback of this method is the high computational effort involved in obtaining a solution.

Bowman (5) and White (36) have proposed integer programming formulations of line balancing problem. In integer programming formulation the number of equations and inequalities rise astronomically as the number of work elements increase. The method of solving the problem is not only tedious because of the size but is also very complex.

Held, Karp and **Shareshian** (11) have offered a method of solving the assembly line balancing problem using Dynamic Programming. They have approached the problem as a sequencing problem involving precedence constraints that prohibit the occurence of certain orderings. The method offers a balance with minimum number of work stations for a given cycle time. Successive approximation has been recommended by Held et. al., for large size problems to reduce enormous computation time involved if solved otherwise. When successive approximation

is made use of, no exact solution is guaranteed. Master's study has revealed that the Held et. al. technique stands out to be the best, resulting in the least idle time among all the ALB techniques. The technique has a limitation in terms of the problem size. As the problem size increases, the computation time increases and so one has to resort to successive approximation.

Gujahr and Nemhauser (10) have developed a mathematical model in which the objective function (minimization of total idle time) is transferred into a "Shortest Route" problem in a network. This network has been constructed in a special way such that there is no need to evaluate the "length" of the various arcs in the network. The computational inefficiency and the computer memory requirements limit the applicability of the algorithm only to small size problems.

All analytical methods (mathematically based) proposed for line balancing problem seem to be impracticable for real life industrial problems. This is due to the fact that the industrial problems are normally large in size and therefore require large amount of computational time. It is unfortunate that at present an answer to this question of practicability does not seem to be available, since there apparently is no formula or prescription on hand to determine the number of feasible orderings for a given problem with a reasonable computation time. In addition, all the analytical models

assume deterministic work elements and equal performance rating for all operators. These assumptions are not valid for most of the industrial assembly lines. It may be concluded that all the analytical methods provide us with a deeper insight and understanding of the problem rather than determining a practically usable solution.

2.1.2 Heuristic Methods

Bryton (4) has presented a procedure for interchanging work elements between stations to reduce the cycle time for a given number of stations. In Bryton's methodology work elements are initially assigned to the various stations and then work elements are interchanged successively between the stations with the largest and smallest work contents. The interchanging of work elements can also be in pairs which can be traded without violating conditions of the precedence restrictions and whose time difference is closest to one half the difference between station idle times. The primary problem with Brytor's procedure is that an extensive amount of search is required before work elements can be traded without violating precedence restrictions. In addition, the initial feasible solution may be a limiting factor on the amount of improvement that can be achieved.

Tonge (32) has proposed a method for balancing assembly lines utilizing heuristic rules for grouping work elements (Phase I), assigning work elements (Phase II), and

transferring work elements among stations to obtain even distribution of work among the stations (Phase III). Tonge has defined three compound elements to be used as the basis for grouping work elements. The compound elements are : chains, sets and Z's. A recursive procedure is used to group work elements into compound elements. The repeated application of grouping procedure results in a hierarchy of simplified problems. Work elements are transferred among work stations until the distribution of work among the stations is as even as possible. Tonge states that the primary purpose of his heuristic rule is to illustrate how some of the problem solving concepts proposed by Newel and Simon (26) may be applied to industrial problems rather than prove that these concepts have any real economic value at present time.

Kilbridge and Wester (16) have suggested a manual method of line balancing. It involves transfer, trading etc., of work elements. The important as well as novel contribution of this method is in the initial setting of work elements. The initial setting highlights the relative range of positions that certain of the less constrained work elements can occupy, and also groups the work elements that can be permitted among themselves. While the methodology relies heavily on intuition and judgement, it eases the job somewhat by providing a framework which directs attention to the most "mobile" work elements.

In the other articles Kilbridge and Wester discuss the balance delay problem (35), review of techniques developed for line balancing (18) and present application of their technique to an industrial assembly line (17).

Helgeson and Birnie's (12) algorithm consists of a heuristic rule that assigns work elements to stations on the basis of work content that follows the work element under consideration. Each work element is given a weight equal to its own time content plus the time contents of all the elements which must follow it. The work elements are ranked and listed in the descending order of weight. An attempt is made to assign the work elements in that order to the first work station. If an element time is greater than the remaining time for the station, then it is passed over in favour of another element farther down the scale, provided that precedence or zoning constraints are not violated. Once a station is filled, the next station is assigned elements starting with the first unassigned work element in that order. This procedure of work allotment does not guarantee optimal solutions and in some cases may lead to very coarse balances. The technique is logically simple, requires little ingenuity and can be applied by persons with little mathematical knowledge. A more detailed description of the method is presented in Chapter 4.

Hoffman (13) has proposed a method of minimizing the idle time at each successive station. He generates all

feasible station assignments that do not exceed the selected cycle time and selects the best arrangement from these with the help of a triangular precedence matrix. The tasks for the first station are selected from the feasible sub-set of tasks such that the idle time for the station is minimum. After the set of tasks for the first station have been selected, the second station is opened. The tasks are assigned in the same manner as was done for station one. New stations are opened and the procedure is repeated till all the tasks have been assigned. The application of Hoffman's procedure results in local minimum which may or may not provide an acceptable solution to the total problem.

Mansoor (19) has illustrated an improvement on the Helgeson and Birnie's ranked positional weight technique. The improvement is brought in by determining the most efficient operating conditions considering all work unit combinations for various cycle times. Mansoor's method flags the ranked positional weight method when idle time gets too high and then it backtracks. Backtracking is done until either a balance with desired number of stations is found or cycle time is incremented. It is claimed by Mansoor that the method would lead to an optimal solution but experience shows that it need not necessarily be so. Moreover, backtracking may prove to be very uneconomical in terms of computation time with some of the problems.

In 1965, Tonge (33) has developed a procedure to cope with the combinatorial aspects of the assembly line balancing by combining a few heuristics probabilistically. The author has emphasized the following heuristics : Choose the task with the largest operation time, choose the task with maximum followers, choose the task randomly. Tonge claimed that the random selection of heuristics for choosing the next task does as well as or better than either use of individual heuristics alone or random choice of the tasks directly without intervening on the choice of heuristics. Arcus (1) has reported a better procedure which is discussed latter in this section.

Moodie and Young (24) have developed a two phase heuristic procedure for balancing assembly lines. In the first phase a preliminary balance is obtained by using largest candidate rule. In the second phase heuristics are used to shift tasks between stations in an attempt to reduce the line idle time. The basis of phase 2 is the work of Bryton (4). Moodie and Young's procedure allows task performance times to be variable. They assume that the task times are independent, normally distributed random variables with known mean and variances. For the case of variable performance times, in phase 2 an attempt is made to equalize the variances between stations. Consideration of variability in performance times is a step in the right direction if a line balancing technique

is to be adopted for industrial assembly lines. The effect of variability in performance times on the solution is presented in detail later in this chapter. The extensive searching procedure involved in the methodology forbids its application to large scale balancing problems.

Arcus (1) has presented a technique that samples feasible sequences of work elements and assigns work elements to stations in the order indicated by the sequence. The sequence which incurs the least amount of idle time is selected to be the solution. In his first approach the work elements are selected randomly. However, to improve the results he introduced bias into the selection by weighting the work elements. Five weights have been developed and employed. As an alternative approach Arcus has tried to load the stations maximally before passing to next station. Arcus' technique stands out to be the best for large assembly lines in view of the computational hazards for Held et. al. (11) technique. A detailed discussion on Arcus' methodology is given in Chapter 5.

In 1968, Mansoor (21) has developed an algorithm to take care of variable performance levels. Mansoor in his approach firstly establishes the minimum number of work stations, the cycle time and then selects suitable operators to man the job. He calculates the amount of work each operator can perform and then assigns work elements to meet the precedence restrictions and operator capacity. By trying to take care of the performance levels, Mansoor has definitely gone a step ahead

of other researchers in balancing real life assembly lines. However, the determination of the solution requires a lot of backtracking and so the computer time required becomes considerably high.

Ramsing and Danning (27) have extended Helgeson and Birmie's algorithm to account for the variations in operation times. Except that they tried to account for the variability in service times, the algorithm is the same as that described by Helgeson and Birnie.

The main objective in all the above heuristics is to reduce amount of search needed to solve the problem. The heuristic procedures substitute the effort-reduction for guaranteed optimal solution of an analytical method. The heuristics have proved useful in balancing a variety of assembly lines. They require a little ingenuity and a basic knowledge of arithmetic. Therefore, these techniques and the obtained solutions are easily understood by the line supervisors. The heuristic procedures normally yield more than one solution to the problem and this gives some latitude in the hands of the line supervisor to alter the sequence of work elements without disturbing the optimal balance.

2.2 Mix - Model Assembly Line Balancing

Wester and Kilbridge (34) were the first to propose a methodology for mixed model ALB in 1964. They have presented two basic approaches for the optimal sequencing of models or a

mixed model assembly line. Each of the proposed approaches tries to accomplish effecient use of assembly man-power and avoidance of congestion by carefully sequencing the models. Launching of models in one case is done at variable rate (Variable Rate Launching) and in other case at a fixed rate (Fixed Rate Launching). Kilbridge and Wester have assumed that total work for each model is evenly divided among the operators, the work stations are adjacent and non-overlapping and each station is manned by only one operator. Because of these assumptions the model holds good only for hypothetical situations and is not applicable for solving practical problems.

Thomopolus (31) has developed a procedure for adopting a single model line balancing technique to mixed model balancing. By defining various inefficiencies and the costs associated with them, Thomopolus suggests a methodology to sequence the models in such a way that the total cost of inefficiencies resulting from scheduling a unit of a given model is kept at minimum. Because the line balancing and sequencing procedures consider a variety of factors, they are applicable to many types of assembly lines. Thomopolus' approach to model-mix problem looks more exhaustive than the study by Kilbridge and Wester.

Roberts (29) has used an integer programming approach for solving a multi-model balancing problem. A network analogous has been applied to mixed-model line balancing problem. Roberts

has given only a theoretical formulation. No mention has been made regarding its computational feasibility or application to industrial problems.

Only a beginning has been made for solving the model-mix problem. All the methodologies are based on the basic assumption that various models have been balanced individually. This may not be a correct assumption though it simplifies the problem to great extent. Effect of balance-delay on model launching is thus totally ignored. The assumption of constant performance time and equal operator performance level further reduce the applicability of these models for industrial problems.

2.3 Scope for Present Investigation

2.3.1 Service Time Variability

Moodie and Young (24) and Ramsing, and Dawning (27), analyzed the ALB problem with the assumption that the service times are probabilistic. As has already been pointed out, the Moodie and Young's method suffers from computational inefficiency and Ramsing and Dawning's method produces very coarse balances. Other researchers have either completely ignored the variability in service times or assumed it to be compensated by delay allowances. Nevertheless, due to the human element which is always present in the assembly of operations, the time necessary to perform a work element is hardly deterministic. Many factors like difficulties in

fitting parts, design of the work place, the speed and sharpness of tools, and the effort, attention and methods of workers affect the performance of the operator. If average work element times are used for line balancing, then on an average fifty percent of the items will not be finished within the cycle time, causing serious hold-ups of the line. Clearly, if sound balances are to be produced for assembly lines the variability factor should be considered.

The following are some of the possible ways which can provide solution to the variability problem:

i. Provision of inter-stage buffers between stations,

ii. Maintenance of utility workers,

iii. Provision of allowance for variability in cycle time.

Intermediate storage between stations reduces the loss of productivity which results from stochastic variations in work element times. Provision of inter-stage buffers makes the work stations independent of each other and this results in an increase in the efficiency of the assembly line. The provision of finite buffer capacity between successive stations may not be always feasible due to practical considerations. For example, in a continuously moving conveyor belt there can not be a provision for intermediate storage space. Under situations when intermediate storage is practical, one should keep in view that the buffers involve sizable costs in terms of locked capital.

Due to stochastic variations in work element times, sometimes the operator has to cross the downstream work limits to complete the work. Under such a situation, a utility worker may be needed to take care of the additional work to be performed at this station. The proposition of maintaining an utility workers does not seem to be a worthwhile proposal for two reasons. The number of utility workers may be so high that it may not be economical to employ a utility workers. Moreover, the effective utilization of utility workers time would be very difficult in large lines.

The variability in work element times can also be accounted for by providing an allowance at each work station. The magnitude of allowance at each work station depends on the work elements alloted to this station. The probability of the operation time falling above the cycle time is reduced due to the provision of this allowance. This results in a better productivity because the visual loss in production due to this allowance is more than offset by the increase in production resulting from less hold-up time. An allowance of this type when provided at each work station helps in gaining the confidence of the workers. Further, it provides a very well balanced line with predictable assurance that each operator will complete his or her job within cycle time. Keeping in view the merits of this procedure, a methodology accounting for this feature has been developed in this dissertation.

2.3.2 Variable Operator Performance Level

It is a well known fact that different people have different capabilities to do a task. Therefore, the operators working on an assembly line have different levels of performance. If an ssaumption is made that the performance level of all operat rs is the same, a worker with low performance level would take more time than a worker of higher performance level. If a line is balanced based on this assumption some workers would be taking more and some less than the stipulated time. This causes the line to be unbalanced. Thus, it is logical to distribute the assembly work operations among the operators so that each operator, as far as possible, completes his work within the given time. One attempt made to take care of this factor was by Mansoor (21). But Manssor's methodology applies only for deterministic work element times case.

If the above two factors are neglected a non optimal solution is being sought to the line balancing problem. Incorporating the above two factors would not only produce better balances but also increases the predictability of the results. Though the introduction of unequal abilities and probabilistic element times complicates the line balancing problem, the assumption that these are negligent does not give optimal or near optimal and implementable solutions to the line balancing problem. Therefore, the increase in time and effort involved by relaxing the assumption is worthwhile.

CHAPTER 3

MATHEMATICAL FORMULATION

This chapter is divided into four sections. Section one is exclusively devoted to the expla nation of the important terms in line balancing. Section two contains the nomenclature of the terms explained in section one. The problem statement is introduced in section three and finally in section four, the mathematical formulation is presented.

3.1 Terminology

Work Station : An assigned location or zone where a designated amount of work is performed. A work station is usually manned by one operator but it is possible that stations have more than one operator.

Station Work Content : The amount of work assigned to a specific station on the assembly line. The total work content of any station is equal to the summation of the mean time values of work elements alloted to the station and an allowance for work element variability.

Work Element : The minimum rational division of the task. This is natural minimum time unit beyond which the work can not be logically divided.

Cycle Time : The time period for which a unit of product being assembled is normally available to an operator performing his assigned work. For a given conveyor speed the cycle time will be constant. Cycle time can be thought of as an

elapsed time between successive units passing a given point on the assembly line. The cycle time is usually pre-determined by management in order to achieve a desired productive output within a given period of time.

<u>Delay Time or Idle Time</u> : It is the difference between the time that the part stays at a work station and the time allowed for performing the necessary work. In other words, idle time is the difference between the cycle time and the station work content.

<u>Cumulative Idle Time</u> : The amount of productive time lost along the assembly line because of an imperfect division of work among the work stations is called the cumulative idle time. It is the summation of the idle times at every work station on the assembly line.

<u>Idle Time Ratio</u> : This is the ratio of the cumulative idle time to the total work content on the line for the product.

<u>Types of Balancing Restrictions</u> : The restraints to the balancing problem can be grouped into the following **two** categories :

i. Precedence relations : The technological ordering of the work elements needed to produce a product.

ii. Positional restrictions : The restrictions imposed upon the position of the operator or product while assembly of the product.

Precedence Graph or Diagram : This is a graphical display of precedence relations in a line balancing problem. Products may often be assembled in many different ways because of the commutability relationship of the work elements. A precedence diagram shows all possible feasible ways of ordering the work elements. For a large complex line, the precedence diagram can get out of hand due to large number of work elements involved. In suchacase one may proceed by "Chunks", selecting the major sub-assemblies first to draw the precedence diagram and then proceeding with the other sub-assemblies. Prenting and Batlign (25) have given a detailed description of steps involved in making a precedence graph.

Labour Pool : A labour pool is one containing operators with equal performance level or equal rating.

Operator Rating : This is a measure of an operator's average rate of working. In this study, the work performance level or operator rating is specified in terms of British Standards Institution Scale (6).

3.2 Nomenclature for Mathematical Formulation

The following notations have been used for the mathematical formulation.

i - work element identification number $1 \leq i \leq N$

N - total number of work elements on the line

k - work station identification number $1 \leq k \leq K$

K - total number of work stations on the line

C - cycle time

H - assembly hours per shift

P - production volume per shift

E_i - standard performance time of work element i

V_i - variance of work element i

S_k - work content alloted to station k

r - constant multiplier to standard deviation

d_k - idle time of station k

D - cumulative idle time of the line

j - labour pool identification number $1 \leq j \leq M$

M - total number of labour pools

N_j - number of operators in labour pool j

R_j - rating of operators in the j^{th} labour pool

$\overline{R}(M)$ - average rating for a group of M operators.

P_k - Prob $(S_k \leq C)$, probability of the station operation time S_k falling within the cycle time. Indirectly, it is a measure for reliability of station k.

P_s - reliability of the assembly line system

W_j - allowable work load for an operator in the j^{th} labour pool.

3.3 Problem Statement

An assembly line balancing problem involves a set of work elements which have some kind of precedence relationships among them. The various work elements have probabilistic

time contents which can be approximated by a statistical distribution. The objective, in general, is either to minimize the number of work stations for a given cycle time or to minimize the cycle time for a given number of work stations. The problem is to balance the assembly line using the following information.

Given :
i. Cycle time or number of work stations.
ii. The work elements and their precedence relationships.
iii. The mean time and variance of various work elements.
iv. Level of confidence desired for the completion of work at each work station.

Constraints:
i. Each work element is alloted to one and only one work station.
ii. For desired level of confidence, the sum of the work element times plus associated variabilities do not exceed the cycle time.
iii. Precedence restrictions are not violated.

Assumptions:
i. There are no zoning constraints.
ii. Each work station is manned by only one operator.
iii. The operation time values are distributed in a pattern that approaches normality closely enough so that statistical inference

based on normal distributions of random variable may be employed.

iv. The time contents of the various work elements are independent of each other.

v. The work element variance at a work station is the sum of the variances of work elements alloted to that station.

The last three assumptions have already been justified in the literature. Hicks and Young (14) subjected the time study data for the analysis of variance and concluded that the assumption of normality for time study data was reasonably safe. Buffa (5.6) presents information on studies that show that interaction among motion elements does not have a significant effect on their additivity.

3.4 Mathematical Formulation

The mathematical formulation is divided into two parts In the first part, it is assumed that the operators have same performance levels and the work element times are probabilistic. The objective is to minimize the number of stations for the given cycle time. In the second part variable performance level and probabilistic work element times are considered. In this case, the objective is to minimize the cycle time for a given number of work stations.

The cycle time is determined by dividing the assembly

hours per shift by the desired production volume per shift.

Mathematically $C = H/P$

The determination of cycle time is usually a management decision variable which depends on the production requirements. In the first formulation work element times are considered as probabilistic. Here the objective is to keep the cycle time constant and minimize the number of operators. The second formulation is based on the probabistic work element times and variable operator performance levels. In this, an attempt is made to minimize the cycle time for the given number of operators.

3.4.1 Constant Operator Performance Level

A constant operator performance level for all the operators means that all the operators are 100 percent efficient. This implies that the cycle time for each operator can be kept the same. The total amount of work alloted to each operator has to be equal to or less than the line cycle time. In this case the line cycle time and the work load allowed for each operator are the same. Further, based on the assumptions of normality and independence of work elements, one can say that the station operation time will also follow a normal distribution with variance equal to the sum of the variances of work elements alloted to the work station. Figure 3.1 gives the assignment of work elements to station k when work elements are probabilistic.

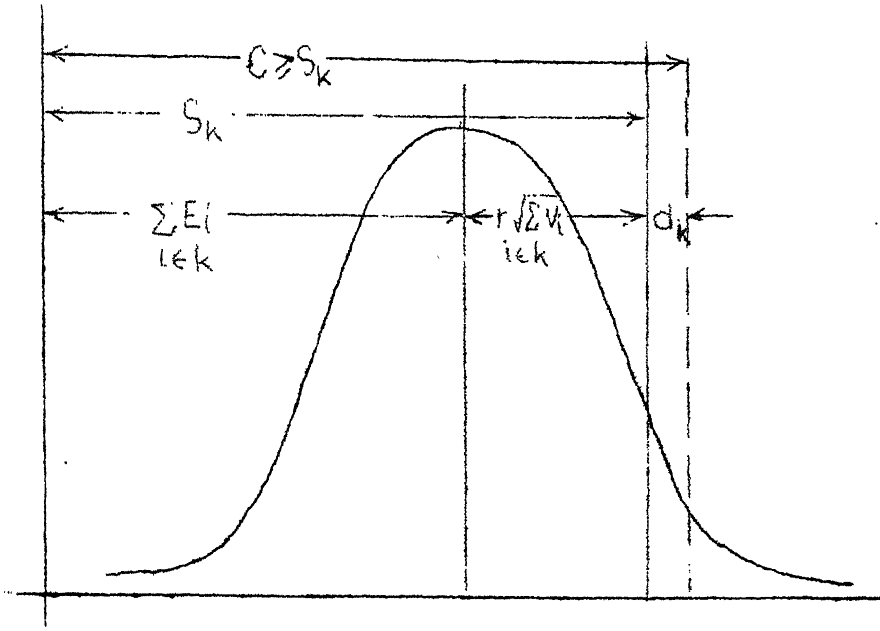


Fig. 3.1 Assignment of work elements to station k.

It is seen that the station time,

$$S_k = \sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \tag{3.1}$$

and

$$S_k \leq C \tag{3.2}$$

i.e.

$$\sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \leq C \tag{3.3}$$

The station idle time,

$$d_k = C - \left\{ \sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \right. \tag{3.4}$$

and total idle time,

$$D = \sum_{k=1}^{K} dk = \sum_{k=1}^{K} C - \left\{ \sum_{k=1}^{K} \left[\sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \right] \right\}$$

$$= CK - \left\{ \sum_{k=1}^{K} \left[\sum_{i \in k} E_i \right] + r \sum_{k=1}^{K} \left[\sqrt{\sum_{i \in k} V_i} \right] \right\} \tag{3.5}$$

The term to the right of CK is a constant for a given line. Therefore;

$$D = CK - \text{constant.} \tag{3.6}$$

For a given cycle time, minimizing the balance delay amounts to minimizing the work stations or the number of workers on the line.

The term $r\sqrt{\sum_{i \in k} V_i}$ is an allowance provided for probabilistic work element times. The allowance provided at each station depends on the work elements alloted to the station and the level of confidence desired at the station. Let r be a factor whose value depends on the desired level of confidence. If a manager wishes that 97.73% of the times the work assigned to a work station is completed within the cycle time then the value assigned to r is 2. Therefore in this case the sum of the average times for the elements assigned to the work station should be equal to or less than the cycle time minus two times the sum of the square Root of variances of the elements assigned to the station. The allowances for various stations would be different for the following two reasons.

i. The amount of variability imbedded into various work elements may not be the same.

ii. The number of work elements alloted to the stations may not be equal.

In other words, instead of providing a standard percentage of allowance for all operators on the line, the station allowance

depends upon the particular combination of tasks assigned to that station. The value of 'r' can be obtained from a table of areas under the normal curve.

3.4.2 Variable Operator Performance Level

The formulation presented in this section is based on relaxing the assumption of constant performance level of operators. In this formulation the number of workers and their respective ratings are assumed to be known. The objective is to minimize the cycle time for the given number of operators.

The best solution to the problem would emerge if one could distribute always the total work contents among the operators such that each operator gets total work load which he can complete within the cycle time.

Let the total labour be divided into M labour pools, then W_j the load allowed for the operator in j^{th} labour pool is given by

$$W_j = C * \frac{R_j}{\overline{R}\ (K)} \qquad \text{where} \quad j = 1, 2, \dots M \qquad (3.7)$$

The value of $\overline{R}$ (K) is calculated using the expression

$$\overline{R}\ (K) = \frac{1}{K} \sum_{j=1}^{M} R_j * N_j \qquad (3.8)$$

If an operator from labour pool j is selected to man the k^{th} station then the equations 3.1 and 3.2 get modified to

$$S_k = \sum_{i \in k} E_i + r \sqrt{\sum_{i \in k} V_i} \qquad (3.9)$$

and $$S_k \leq W_j \tag{3.10}$$

where W_j is calculated from equation 3.7

Then $$\sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} = W_j \tag{3.11}$$

The station idle time and the total idle time can be expressed as

$$d_k = W_j - \left\{ \sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \right\} \tag{3.12}$$

$$D = \sum_{k=1}^{K} d_k = \sum_{j=1}^{M} W_j * N_j - \sum_{k=1}^{K} \left\{ \sum_{i \in k} E_i + r\sqrt{\sum_{i \in k} V_i} \right\} \tag{3.13}$$

The second term on the right hand side of equation 3.13 is a constant for a given line. Therefore,

$$D = \sum_{j=1}^{M} C \frac{R_j}{\overline{R}(K)} * N_j - \text{constant} \tag{3.14}$$

From eq. 3.8 $$= \frac{1}{\overline{R}(K)} \sum_{j=1}^{M} R_j * N_j = K \tag{3.15}$$

Therefore

$$D = CK - \text{constant} \tag{3.16}$$

Thus, for a given number of work stations minimizing the balance delay amounts to minimizing the cycle time.

So far, we have confined ourselves to the problem of building reliability into the work stations. However, a manager is more interested in the reliability of assembly line system

as compared to the reliability of individual work station. The assembly line system consists of a large number of work stations in series. This means that if the work station time for any work station falls above the cycle time, the system is disturbed. The reliability of the assembly line system is expressed as the product of the reliability of all the work stations on whose satisfactory operation the system depends for its survival. For 'K' work station in series, the system reliability is given by

$$P_s = P_1 \cdot P_2 \cdot P_3 \dots P_K = \prod_{i=1}^{K} P_i$$

In the next few chapters methodologies to solve the above structured problems are presented. In Chapters 4 and 5 procedures for solving the ALB problem with probabilistic work element times and equal operator performance are presented. In Chapter 6 an attempt is made to present an approach to handle ALB problem with probabilistic work elements and variable operator performance.

CHAPTER 4

MODIFIED RANKED POSITION WEIGHT TECHNIQUE

4.1 Introduction

In this Chapter, an AIB methodology which accounts for variability in work element times is presented. The methodology utilizes the basic concepts of Helgeson and Birnie's (12) RPW technique. A new method for calculating positional weight is proposed and concepts like Forward and Backward Balancing, and Balancing Matrix are introduced as aids for solving large scale industrial assembly lines effectively. Before presenting the methodology it would be worthwhile to analyze some of the important characteristics of AIB problems and present a critical examination of RPW technique.

4.1.1 Characteristics of AIB Problem

The key idea in line balancing is to put the work elements in some executable order, either before they are assigned to the stations or as they are assigned. An ordered arrangement of 'N' work elements that can be performed in that order is called a feasible sequence. 'N' work elements can be arranged in N! distinct sequences. However, because of precedence relations only some of these N! sequences will be feasible. If there are 'r' precedence relations among the 'N' work elements, then there are roughly $N!/2^r$ distinct feasible

sequences. For example the estimate for the number of feasible sequences is $8!/2^{10} \approx 44$ for the eight element problem whose precedence-graph is given in Fig. 4.1.

A feasible sequence can be turned into a balance in the following way. Assign the work elements to work stations in the order given by the sequence. After several work elements have been assigned it will be found that the next one in the sequence will not fit into the first work station because of the cycle time restriction.

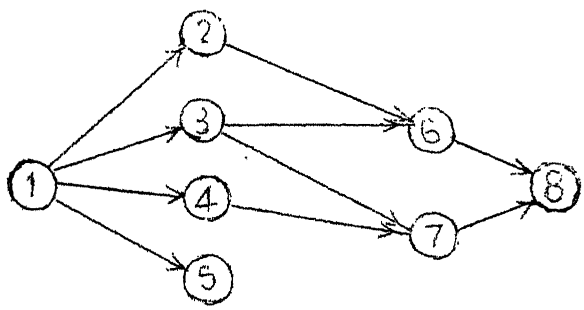


Fig. 4.1 Precedence Graph - eight element problem.

This work element becomes the first in the second station and the process is continued until the next work element will not fit into the second station. This work element becomes the first one in the third work station and we continue in this way until all the 'N' work elements have been assigned.

If all the feasible sequences are evaluated, the sequence which requires minimum work stations becomes the optimal balance. It should be noted that two different sequences may require the same number of work stations. Therefore,

there can be more than one optimal solution to a line balancing problem. An optimal solution is guaranteed if all the feasible sequences are evaluated. But enumeration of all feasible sequences is quite complex because the number of feasible sequences increase at a very high rate as the number of work elements increases. For, as few as fifteen work elements without precedence constraints, Arcus (1) reported that the number of feasible sequences would be 1, 307, 674, 368,000 - the examination and evaluation of which is beyond the life span of a man or a computer. Generation of finite number of feasible sequences is the only alternative. However, if a finite number of feasible sequences are generated there will be a probability associated with getting an optimal solution.

4.2 Ranked Positional Weight Technique

In the ranked positional weight technique proposed by Helgeson and Birnie (11), each work element is assigned a positional weight. The selection of work elements for assignment to the various work stations is done by using biased positional weights of the work elements. A single sequence which is taken as the solution to the ALB problem is constructed. The positional weight of an element is the sum of its standard performance time and the standard performance times of all work elements which must follow it. After calculating the positional weights the elements are ranked. Keeping in view the cycle time and precedence constraints the elements

are alloted to the work stations in the descending order of the positional weights. Helgesan and Birnie (12) did not explicitly give the logic behind the determination of positional weights. The procedure of assigning the work elements with the largest weight first, seems to be quite logical because the element with the largest weight is likely to have either highest number of followers or followers with large standard performance times. If this element is selected, it is likely to span larger list of elements for allotment or is likely to make available elements with large standard performance times.

In 1970, Ramsing and Downing (27) tried to extend the ranked positional weight technique to assembly lines with variable element times. Ramsing and Downing incorporated Moodie and Young's (24) variable station assignment concepts into the line balancing problem. The ranked positional weight technique was used for alloting the work elements to the stations. This approach suffers from the shortcoming mentioned below.

As is seen from above, in the RPW technique, only two inputs vary as one progressively constructs a sequence, the work elements standard performance time and the number of work elements which subsequently follow each work element. The variability in work element times is totally neglected in the weighting procedure. If variability in work element times is also considered in calculating positional weights, work elements

with high variability get selected initially and also there are chances of elements with high variability becoming available early as one progressively constructs a sequence.

4.3 Conceptual Inputs For Methodology

The following concepts have been introduced for the development of the proposed methodology.

4.3.1 Modified Weighting Procedure

As has already been mentioned, variability in work element times is an important factor and therefore should be included in the weighting procedure for getting better balances. In order to incorporate variability, in addition to work element standard performance time, it is logical to include the effect of variability while calculating the weight. The modified method of weighting the work elements would then be

"Weight elements by the standard performance time plus a value obtained by multiplying the square root of the work element time variance by a constant for the element under consideration and all the elements that follow it."

Mathematically, $$W_i = \sum_{j=1}^{f} \left\{ E_j + r\sqrt{V_j} \right\}$$

where W_i is the weight attached to element i and f elements follow element i.

The logical inclusion of the variance term in weighting has the following advantage. An element with the largest

weight, in the modified method of weighting, has elements with large variability and elements with large standard performance time as its followers. This enables the early selection of work elements with large variability and large standard performance time. The effect of loading large elements is benificial because by loading large elements first, the small elements are then available for packing in the reduced space.

4.3.2 Forward and Backward Balancing

The conventional method of looking at the assembly line while balancing is from the start of the line to the end of the line. An element with no precedents is allotted to the first work station. The criterion of alloting work element without any precedents to station may be termed as "forward balancing". The other way of looking at the line would be from the end of the line to the beginning of the line. In that case, work elements with no followers are allotted to the last work station and the sequence is constructed from the end of the line. The method of constructing sequences with no followers is termed as "backward balancing". Solutions obtained by forward balancing and backward balancing need not be improvements over one another. The alternative solutions provide a simple and convenient means for determining whether better solutions are likely to exist or not. In forward balancing the work elements with the highest positional weight are

given first preference while in the case of backward balancing work elements with lowest positional weight are given first preference.

4.3.3 Balancing Matrix

The balancing matrix is an extension of the precedence matrix introduced by Hoffman (13). Hoffman's precedence matrix takes care of only the immediate followers whereas in balancing matrix all the elements that follow are shown.

The balancing matrix is a square matrix in which the rows and columns are labelled with consecutive element numbers. Entries in the matrix are made in the following manner.

i. If the element of row i is followed by the element of column j, a "1" is placed in row i and column j.

ii. All other entries are zeros.

The balancing matrix for the eight element problem depicted in Fig. 4.1 is given in Table 4.1.

Table 4.1 Balancing Matrix - eight element problem.

i \ j	1	2	3	4	5	6	7	8
1	0	1	1	1	1	1	1	1
2	0	0	0	0	0	1	0	1
3	0	0	0	0	0	1	1	1
4	0	0	0	0	0	0	1	1
5	0	0	0	0	0	0	0	0
6	0	0	0	0	0	0	0	1
7	0	0	0	0	0	0	0	1
8	0	0	0	0	0	0	0	0

The important features of balancing matrix are

i. The balancing matrix is an upper triangle matrix. This will always be true if lower numbers go into higher numbers and also if there are no contradictory precedence relationships.

ii. If the column corresponding to element i has all zeros, it indicates that the element doesn't have any precedents. For example element "1".

iii. Similarly if the row corresponding to element i has all zeros, it indicates that the element does not have any followers. For example elements "5 and 8".

In the following section a step by step procedure for the methodology using the above concepts is presented.

4.4 Methodology

For forward balancing, the assignment of the elements to various work stations is made according to the following steps:

Step 1 : Determine the positional weights of all the work elements on the line. This can be done by keeping '1' along the diagonal of the balancing matrix and multiplying it with a column vector containing the standard performance time plus a constant times the square root of element time variance. '1's are placed along the diagonal of the balancing matrix to

take care of the element time and variance of the elements under consideration in addition to its followers while calculating the positional weight.

Step 2 : The elements are ranked and rearranged in decreasing order according to their positional weight.

Step 3 : Select the work element with the highest positional weight and assign it to the first work station.

Step 4 : Calculate the station time for the first work station. If element i is allotted, the station time would be

$$S_1 = E_i + r \sqrt{V_i}$$

Step 5 : In the balancing matrix, plug zeros in all the cells of the row corresponding to the assigned work element.

Step 6 : Select the work element with the next highest positional weight and attempt to assign it to the work station under consideration after making the following checks.

(a) Check whether the precedents of the work element have already been assigned. This can be checked from the balancing matrix. If the column corresponding to the work element contains all zeros, the element does not violate the precedence constraints. If a '1' is

encountered in the column, it indicates that one of the preceding elements has not yet been allotted. If the preceding elements are all alloted, go to step 6b. Otherwise go to step 8.

(b) Check if the following condition is satisfied,

$$\sum_{i \in k} E_i + E_j + r\sqrt{\sum_{i \in k} V_i + V_j} \leq C$$

where i work elements are allotted to station k. If the above condition is satisfied go to step 7, otherwise go to step 8.

Step 7 : Update the station time to

$$\sum_{i \in k} E_i = \sum_{i \in k} E_i + E_j \text{ and } \sum_{i \in k} V_i = \sum_{i \in k} V_i + V_j$$

where j is the work element selected for allotment to station k. Go to step 5 to eliminate the assigned element as a precedent to the unassigned elements.

Step 8 : Keep going to step 6 till one of the following conditions is satisfied :

a. All work elements have been assigned.

b. No work element remains that can satisfy both precedence requirement and can fit in the work station under consideration.

Step 9 : Assign the unassigned work element with the highest positional weight to the next work station and go through steps from 6 to 8 till all the work elements are alloted.

For the backward balancing, the same procedure is followed except for the following differences :

i. Elements with lowest positional weight are assigned first.

ii. For the element under consideration for assignment, instead of checking for unassigned precedents, a check is made to see if it has any unassigned followers. In step 6 (a), we check for a row of zeros instead of a column of zeros.

iii. The column corresponding to an assigned work element is made of zeros rather than the row corresponding to an assigned work element. In step 5 the plug zeros corresponding to assigned work elements column.

4.5 Results and Discussion

A computer programme written in FORTRAN IV has been developed for the methodology. The programme in its present form consumes 32 K of computer memory and can handle assembly line having upto 120 work elements.

Four assembly line problems were tested using the proposed approach. The four problems are :

i. Assembling clothes problem

ii. TV Main chassis assembly problem

iii. Refrigerator final assembly problem and

iv. Truck assembly problem.

The Assembly Clothes problem is due to Kilbridge and Wester (16). The precedence graph for this problem is given in Appendix A, Fig. A-1. Appendix A also gives the description of the work elements and the standard performance time and variance of these work elements. Kilbridge and Wester dealt with this 45 element problem with deterministic work elements. The work element variance are generated randomly. In view of lack of information on cycle time, a value of 207.8 secs. was selected to keep the number of work stations to three on the line.

The TV Main Chassis problem is the outcome of a study conducted by the author for an Electronics Industry manufacturing a popular brand of TV's. The TV Main Chassis assembly forms the major assembly line in the TV plant. Keeping in view the importance of Main Chassis assembly for a TV manufacturing industry, this study was undertaken. Fig. B-1, in Appendix B gives the precedence-graph for the TV Main Chassis assembly problem. The detailed description of the 97 work elements, their standard performance time and variances are given in Appendix B. The management of the TV industry specified a cycle time of 6.5 minutes to meet their production requirements.

The Refrigeration final assembly problem is also the outcome of the author's study of a home appliances industry manufacturing a reputed brand of Refrigerators.

Unlike the TV industry the home-appliances industry has a very long line. The important features of this problem are a short cycle time of 154 secs. (2.57 min.), high standard performance times for the work elements and a high work element time variance. The description of the 96 elements involved in the manufacture of the Refrigerator are given in Appendix C, and their precedence relationships in Fig. C-1.

The 111 element problem is given in Appendix D is due to Arcus (1). This problem has been selected in view of its size. It is the biggest problem encountered in literature. The element variances are generated randomly as was done for the Assembly Clothes problem. It is not possible to give the description of the various work elements because Arcus in his article did not provide this information. In Appendix D the precedence graph (Fig. D-1) and the element times are given. For this study an arbitrary cycle time of 68 secs. has been selected because this information is also missing in Arcus' thesis.

Table 4.1 gives the solution obtained by using the proposed methodology on clothes problem. The execution time was 0.9 secs. The following inferences can be drawn from the table. Although the cycle time is 207.8 secs., the work station time does not exceed 206.54 secs. The line idle time is 206.57 seconds which is apparently a very high value

keeping in view the cycle time of 207.8 secs. Element 45 was only left for allotment to fourth work station. The idle times of 1.63 secs., 1.26 secs., and 1.27 secs. at stations 1, 2, and 3 respectively leads one to believe that there could be a better sequence which requires lesser number of work stations. By increasing the cycle time further we may get a solution having three stations using the same methodology.

The methodology fared very well with the TV problem. It yielded an 11 work station solution with a line idle time of 0.97 minutes. It took 3.2 secs. of computer time to get the solution. In view of the low idle time with the solution, there does not seem to be a possibility for getting a better solution. The balance obtained for the TV problem is presented in Table 4.2.

The proposed approach did not yield very satisfactory results with either the Refrigerator problem or the Truck problem. The high idle times of 177.17 secs. for the Refrigerator problem and 108.27 secs. for Truck problem suggested that better balances may be present for these problems. As is the case with the previous problems, the execution times for these problems are also low - 2.8 secs. for Refrigerator problem and 3.2 secs. for Truck problem. The results for these two problems are presented in Tables 4.3 and 4.4.

TABLE 4.1

Solution to Assembling Clothes Problem using Modified RPW

Number of work elements = 45 Cycle time = 207.8 secs.

Total work content = 624.63 secs. Line Idle time = 206.57 secs.

Station reliability = 99.85% Line reliability = 99.59%

Station No.	Elements Alloted to the Station	Station Mean secs.	Station Variance $(sec.)^2$	Station time secs.
1	1, 2, 7, 8, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 24, 27	183.00	59.67	206.17
2	3, 4, 5, 21, 22, 23, 25, 33, 38	177.00	96.98	206.54
3	6, 9, 10, 26, 28, 29, 30, 31, 32, 34, 35, 36, 37, 39, 40, 41, 42, 43, 44	187.00	42.36	206.53
4	45	5.00	0.02	5.39

TABLE 4.2

Solution to TV Assembly Problem Using Modified RPW

Number of work elements = 97 Cycle time=6.5 min.

Total Work Content = 70.53 units Line Idle time = 0.97 min.

Station reliability = 99.85 % Line reliability = 98.60%

Station No.	Elements alloted to the station	Station Mean min.	Station Variance $(min.)^2$	Station time min.
1	1, 11, 12, 15, 16, 18, 21, 22	5.36	0.14	6.49
2	13,14,17,19,20,23,24,25,26,27, 30,31	5.44	0.10	6.39
3	2,3,4,28,32,33,34,35,36	5.32	0.15	6.49
4	5,6,7,8,9,10.29,37,38,39,69	5.59	0.08	6.44
5	40,41,42,43,44,54	5.50	0.07	6.32
6	46,71,90,91,92	4.81	0.23	6.24
7	55,60.61,72,73,74,79,93	5.75	0.06	6.48
8	47,56,57,58,59,62,63,80,81,94,95	5.62	0.08	6.47
9	51,64,65,75,83,86,96	5.19	0.18	6.48
10	45,48,66,68,82,84,87	5.41	0.09	6.31
11	49,50,52,53,67,70,76,77,78,85, 88,89,97	5.66	0.06	6.41

TABLE 4.3

Solution to Refrigerator Problem Using Modified RPW

Number of work elements = 96 Cycle time = 154.0 sec.

Total work content = 3364.83 sec. Line Idle time = 177.17 sec.

Station Reliability = 99.85% Line Reliability = 96.87%

Station No.	Elements alloted to the station	Station Mean sec.	Station Variance $(sec)^2$	Station time sec.
1	5, 6, 7, 11	119.30	106.35	150.24
2	8, 12, 14, 15	113.10	156.71	150.66
3	9, 10. 13, 16	116.00	97.98	145.70
4	1, 2, 3, 4, 17, 18, 19	121.60	84.78	149.22
5	20, 21, 22	118.10	85.14	145.78
6	23, 24, 25, 37	135.90	25.98	151.19
7	26, 27, 28, 35	127.70	75.62	153.79
8	29, 30	112.80	56.84	137.42
9	31, 38	126.83	46.88	147.37
10	39, 40, 41, 42, 47, 48	126.50	73.07	152.14
11	43, 44, 50	119.20	82.78	146.50
12	45, 46, 49, 51, 52, 53	122.20	66.54	146.67
13	54, 55, 60, 61	124.00	32.48	141.10
14	62, 63, 64, 65, 66, 76	130.80	52.10	152.45
15	67, 68, 69, 70, 71, 72, 73, 74	115.60	70.36	140.76
16	32, 56, 75, 77, 78, 79, 80, 81	126.00	47.02	146.57
17	33, 34, 82, 83	121.60	52.93	143.43
18	84, 85	130.20	52.98	152.04
19	90, 91, 92, 93, 94	128.30	41.21	147.56
20	86, 95	115.17	44.04	135.08
21	87, 96	130.50	44.25	150.46
22	57, 58, 89	132.40	33.12	149.66
23	36, 59, 88	109.47	51.76	131.05

TABLE 4.4

Solution to Truck Assembly Problem using Modified RPW

Number of work elements = 111 Cycle time = 68 sec.
Total work content = 1795.73 sec. Line Idle time = 108.27 sec.
Station Reliability = 99.5% Line Reliability = 96.20%

Station No.	Elements alloted to this station	Station mean sec.	Station variance $(sec)^2$	Station time sec.
1	1, 2, 3, 101	49.00	5.31	55.91
2	4, 10, 11	57.49	12.16	67.95
3	7,9,12,13,14,16,18,19,22,24,27, 30,35,43	63.36	2.34	67.95
4	8, 17, 25, 28, 29, 36, 38	62.39	3.30	67.84
5	5,20,34,37,44,45,46,48,49,50,51, 52,53	54.10	12.50	64.71
6	42	56.89	9.43	66.10
7	47, 55	53.25	23.89	67.91
8	23, 54	51.44	17.41	63.96
9	32, 61	43.32	26.02	58.62
10	41, 58, 69	49.78	34.55	67.41
11	56, 66	47.45	30.22	63.94
12	70, 73	55.92	5.87	63.19
13	64, 72, 75	60.29	6.44	67.90
14	74, 76, 78	52.18	21.42	66.06
15	57, 62	54.88	12.66	65.34
16	81, 84, 89	56.25	12.60	66.90
17	77, 80	50.38	25.89	65.65
18	60, 71	51.94	19.79	65.29
19	31, 58, 83	59.78	2.97	64.95
20	91, 92, 93, 94	60.62	0.86	63.40
21	79, 88, 95	61.67	4.41	67.97
22	6, 15, 98, 103, 108	51.08	26.24	66.45
23	39	44.98	33.95	67.46
24	26, 86, 105	51.94	25.38	67.05
25	40, 63, 96	54.39	18.86	67.42
26	21, 87, 97, 100	62.34	2.54	67.12
27	33, 65, 82, 85, 99, 102,104,106,107	61.18	4.80	67.75
28	67, 68, 90, 109, 110, 111	21.70	0.36	23.51

TABLE 4.5

Comparison of proposed methodology with Ramsing and Downing's methodology.

Methodology \ Problem	Assembling Clothes	Truck Assembly	TV Assembly	Refrigerator Assembly
	Number of Work Stations			
Proposed	4	28	11	23
Ramsing and Downing	4	28	12	24

In order to study the influence of adding variability in the weighting procedure, all the four problems were also tested using the Ramsing and Downing's algorithm. It is very interesting to note that the proposed methodology fared better than Ramsing and Downing's procedure for the TV problem and Refrigerator problem. The balances produced by the proposed algorithm needed one station less in both the problems. Ramsing and Downings procedure proved equally effective as the proposed methodology for the other two problems. Table 4.5 gives the comparison of the proposed algorithm with that of Ramsing and Downing. It may be concluded at this juncture that inclusion of variability in weighting procedure aides in getting better balances.

Backward balancing also produced balances requiring the same number of work stations.

Though the methodology yielded results at a very low computation time, the high idle time with three of the four problems made the author to search for better methods. The outcome of the search is the methodology presented in Chapter 5.

CHAPTER 5

METHODOLOGY FOR SOLVING PROBABILISTIC WORK ELEMENT TIMES PROBLEM

5.1 Introduction

It has been observed in Chapter 4 that the Modified Ranked Positional Weight technique provides decent balances efficiently. However, for the three out of the four problems tested, it is found that the idle time is fairly high. This lead the author to believe that there could be balances with fewer work stations and therefore further efforts were made to work for a better line balancing methodology. The concepts of biased sampling appeared to have good potential for generating better balances.

5.2 Critical Analysis of Arcus' (1) Approach

Arcus in his COMSOAL, an acronym for a computer method of sequencing operations for assembly lines, combined a high speed digital computer and sampling concepts in proposing a methodology. It has already been mentioned in the previous chapter that balances can be obtained from feasible sequences. Arcus generated a finite number of feasible sequences and chose the sequence which required the lowest number of stations as the solutions.

If a finite number of sequences are generated there will be a probability associated with getting an optimal

solution. If r is the proportion of feasible sequences which consists of optimal sequences, the probability of the first sequence generated will be optimal is r. The probability that the first sequence will not be optimal is $(1 - r)$. If m sequences are generated the probability that none is optimal is $(1 - r)^m$. The probability that one or more of these m sequences are optimal is $1 - (1 - r)^m$. This probability approaches one, as either r or m increases.

There is no way to determine r except by impracticable enumeration and evaluation of all sequences. Arcus observed that in order to have a higher degree of confidence, the sample size should be high. As the level of confidence for the generation of optimal sequence changes from 0.99 to 0.9999 the sample size increases enormously. As the management needs a solution at a reasonable cost, the computation cost involved in the enumeration of large sequences is pro hibitive. Therefore an economical sample size should be used for the generation of sequences.

Arcus hypothesised that an economical sample size in majority of line balancing problems contained at least one optimal sequence. In a comparatively few assembly lines the sample will atleast have one sequence which will require only one station in excess of optimal number. The results of Arcus justified this hypothesis for an economical sample size of 1000. Therefore throughout this work the sample size for

Instead of generating feasible sequences randomly, Arcus experimented with devices that might bias favourably for the generation of optimal sequence. Tests of Arcus revealed that a product of five of the proposed weights give best results. Arcus concludes that the five weights are to be considered because each weight has some favourable influence for the generation of optimal sequence.

The weight attached to each work element while assigning to a sequence is a product of the weights obtained by the following five rules.

<u>Rule I</u> : Weight work elements that fit in proportion to the standard performance time

Mathematically $W_i = E_i / \sum_{i=1}^{s} E_i$ and $\sum_{i=1}^{s} W_i = 1$

where W_i is the weight attached to i^{th} work element and there are s work elements that fit.

<u>Rule II</u> : Weight work elements that fit by $1/X^1$ where X^1 is equal to the total number of unassigned work elements minus 1 and minus the number of all the work elements which follow the work element being considered

Mathematically $$W_i = \frac{\frac{1}{U - Y_i}}{\sum_{j=1}^{s} \frac{1}{(U - Y_j)}}$$

where Y_j number of work elements follow work elements and U number of unassigned work elements minus one.

Rule III : Weight work elements that fit by number of following work elements plus 1

Mathematically $W_i = \dfrac{Y_i + 1}{\sum_{j=1}^{s} Y_j + 1}$

Rule IV : Weight work elements that fit by the work element time plus the times of all following work elements

Mathematically $W_i = E_i + R_i \Big/ \sum_{j=1}^{s} (E_j + R_j)$

R_i is the sum of work element times that follow.

Rule V Weight work elements that fit by the total number of following work elements plus 1, divided by the number of levels at which those following work elements occupy plus 1.

Mathematically, $W_i = \dfrac{(Y_i + 1) / X_i}{\sum_{j=1}^{s} (Y_j + 1) / X_j}$

where X_j is the number of work elements in the largest chain.

Arcus' methodology assumes that work element times are deterministic. As a first step towards solving the variability in work element times problem, variability concepts were introduced into COMSOAL. The weighting procedure of Arcus was adopted without any modifications. From here onwards the weighting procedure of Arcus is designated by Rule "ARCUS".

5.3 Biasing Procedure For the Proposed Methodology

As a next step towards getting better balances the weighting procedure of Arcus was modified to account for variability. The bias while generating the feasible sequences is based on variability in work element times in addition to the standard performance time and the number of followers for each work element.

In order to incorporate variability in work element times, the following basic rules have been proposed for weighting the work elements.

<u>Rule A</u> : Weight work elements that fit in proportion to the work element time variance.

$$W_i = V_i \Big/ \sum_{i=1}^{s} V_i$$

Mathematically $\cancel{W_i = \sqrt{V_i} \Big/ \sum_{i=1}^{s} \sqrt{V_i}}$ and $\sum_{i=1}^{s} W_i = 1$

where W_i is the weight attached to work element i and s number of work elements are in the fit list.

<u>Rule B</u> : Weight work elements that fit in proportion to the standard deviation of work element time.

Mathematically $W_i = \sqrt{V_i} \Big/ \sum_{i=1}^{s} \sqrt{V_i}$ and $\sum_{i=1}^{s} W_i = 1$

<u>Rule C</u> : Weight work elements that fit in proportion to the standard performance time plus a value obtained by multiplying the square root of element time variance by a constant.

Mathematically $W_i = E_i + r\sqrt{V_i} \Big/ \sum_{i=1}^{s} (E_i + r\sqrt{V_i})$

where r is a constant.

<u>Rule D</u> : Weight work elements that fit in proportion to the standard performance time plus a value obtained by multiplying the square root of work element time variance by a constant for the element under consideration and all the elements that follow it.

$$\text{Mathematically} \quad W_i = \frac{\sum_{i=1}^{s} E_i + r\sqrt{V_i}}{\sum_{i=1}^{f} \sum_{i=1}^{s} E_i + r\sqrt{V_i}}$$

where s is the number of work elements that follow i^{th} work element.

A number of combinations of the above four proposed rules and five rules of Arcus were tried. The following six rules were found to be worth reporting. Each rule has the weighting procedure as a product of the weights obtained by the rules mentioned against them.

<u>Rule P</u> : A I II III IV V

<u>Rule Q</u> : B I II III IV V

<u>Rule R</u> : C II III IV V

<u>Rule X</u> : A I II III D V

<u>Rule Y</u> : B I II III D V

<u>Rule Z</u> : C II III D V

5.4 A General Procedure For Sequence Generation

For generating the biased feasible sequences, the following step by step procedure is followed. Fig. 5.1 is a general logic flow chart for this procedure.

Step 8 : Update the station time to

$$\sum_{i \in k} E_i = \sum_{i \in k} E_i + E_j \text{ and } \sum_{i \in k} V_i = \sum_{i \in k} V_i + V_j$$

where element j is work element selected.

Step 9 : If all the elements have not been allotted, go to step 2. Otherwise repeat the procedure for the required number of sequences by going back to Step 1.

5.5 Results and Discussion

5.5.1 Comparison of Various Rules

A computer package has been developed for the proposed methodology. The programme is written in FORTRAN IV for IBM 7044 computer system. The computer package requires about 16 K of computer memory for a 150 work elements problem. The listing of the computer package named as CALBPROP-I (An acronym for Computerized Assembly Line Balancing with Probabilistic Parameters) is given in appendix F. The variables used in the package are explained in Appendix E. Comment cards have been sprinkled liberally throughout the programme to help the reader in the understanding of the programme.

The four problems which have been tested using the proposed biasing procedures are :

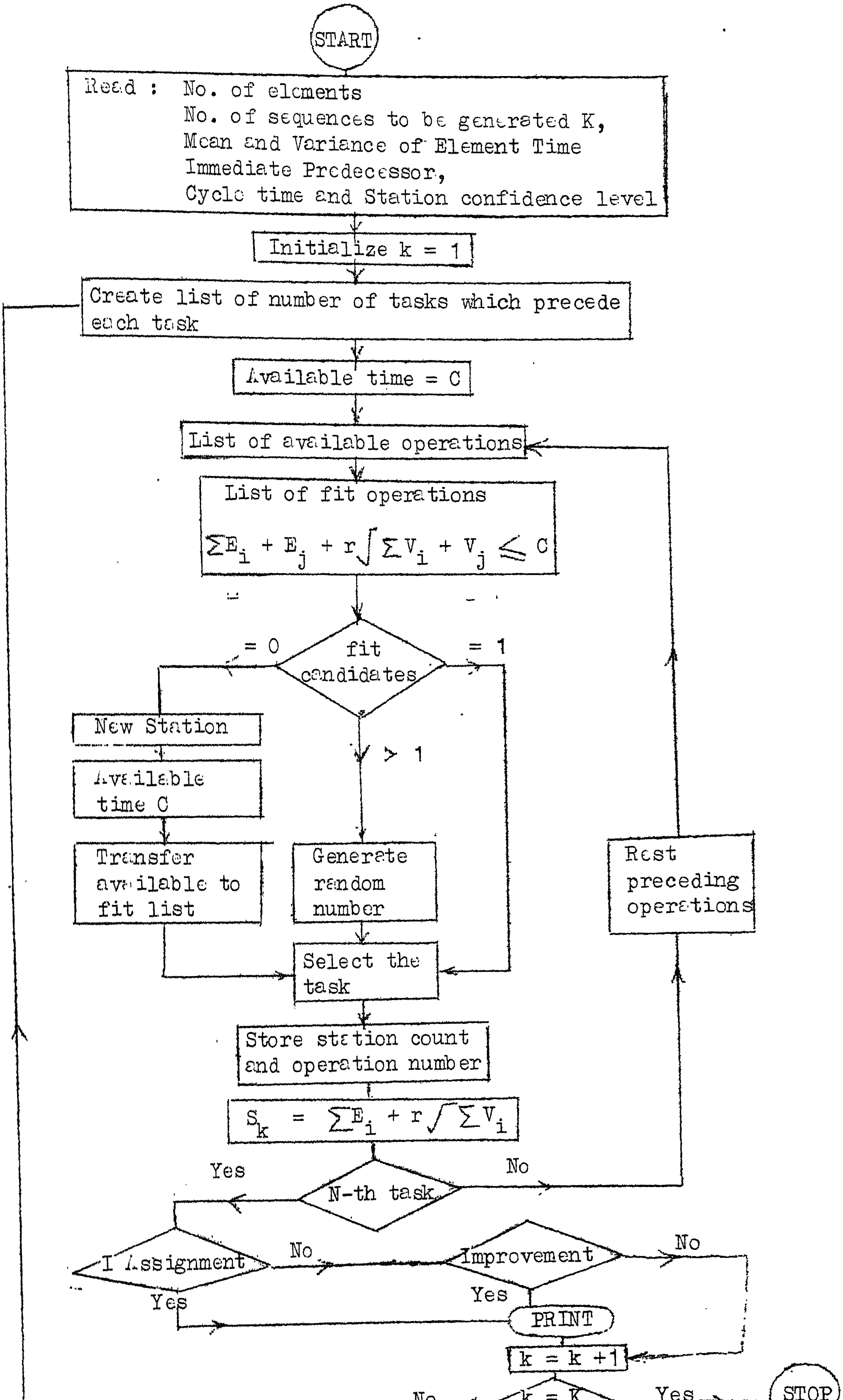
(i) the assembling clothes problem,

(ii) the T.V. main chassis assembly problem,

(iii) the refrigerator final assembly problem and

(iv) the truck assembly problem.

Fig. 5.1 : Logical Flow Chart for Sequence Generation



The details of the above four problems have already been mentioned in Chapter 4. The precedence graph and work element times aregiven in Appendix A, B, C and D.

The inputs to the computer package comprise of

(i) number of work elements,

(ii) mean of work element times and their variances,

(iii) followers for each work element,

(iv) cycle time,

(v) confidence level desired at each work station and

(vi) number of sequences to be evaluated.

The output of the programme contains the following information :

(i) A list containing the station number, the elements alloted to the station and the total work content of the station.

(ii) A frequency distribution of the number of sequences vs required number of work stations.

(iii) Maximum and minimum number of available work elements at each stage of allotment for all generated sequences.

(iv) Mean available work elements at each stage of allotment.

(vi) Mean of mean available operations over all generated sequences.

The results obtained for the above four problems are presented in Tables 5.1 to 5.4.

Station mean is the mean of the frequency distribution of number of work stations vs. the number of sequences requiring this number of work stations. It is to be noted that the generated sequences should require as few work stations as possible in order to obtain an optimal solution. A frequency distribution with a low station mean only indicates the tendency of the biasing procedure in generating more sequences with less number of work stations. Thus a biasing procedure with a low station mean is better than the other procedures.

Operation mean is the mean of the mean number of work elements that become available at each stage of work element allotment. If a high operation mean is obtained by using a particular biasing procedure it indicates that more number of work elements become available at each stage of work allotment. If more number of operations become available at each stage, the probability of generating the same sequence is reduced. If a biasing procedure has a high operation mean and a low station mean it indicates that though the probability of generating the same sequence is reduced, the biasing procedure has a tendency to generate sequences requiring low number of work stations. The author feels that this is a very good property for a biasing procedure.

The expected time for the generation of an optimal sequence is obtained by dividing the total execution time by the number of optimal sequences generated. To many, this may not appear to be an agreeable concept. This concept has essentially been borrowed from scheduling theory. It should be noted that the expected time for generating an optimal solution can be treated as a measure of the computational effectiveness of a biasing procedure.

For the assembling clothes problem rule P turned out to be the best followed by rules X and Q in computational efficiency. The results of this problem are presented in Table 5.1. The station mean is the same for rules P, X and Q, but the operation mean is substantially high for rule Q compared to rules P and X. It is to be observed that rule Q fared better than rule Arcus in every respect.

For the T.V. main chassis assembly problem the results are presented in Table 5.2. For this problem rule X turned out to be the best followed by P and Q in computational efficiency. But when judged from the properties of low station mean and high operation mean, rule Q is certainly the best.

Table 5.3 contains the results of refrigerator final assembly problem. The results indicate that rule Q is the most efficient in computational effectiveness. Further, this rule gives low station mean and high operation mean.

TABLE 5.1

Comparison of Rules Arcus, P, Q, R, X, Y and Z

Assembling Clothes Problem

Number of work elements = 45 Cycle time = 207.8 secs.

Rule	Arcus	P	Q	R	X	Y	Z
3 Stations	8	9	9	9	9	3	3
4 Stations	992	991	991	991	991	997	997
Station Mean	3.992	3.991	3.991	3.991	3.991	3.997	3.997
Operation Mean	6.187	5.238	6.268	6.980	5.232	6.222	6.985
Total Execution Time in Seconds	260	207	242	264	212	240	269
Expected time for one optimal solution in Seconds	3.25	2.30	2.70	2.93	2.38	8.00	8.97
First optimal sequence Number	187 ~~260~~	264 ~~207~~	101 ~~242~~	50 ~~264~~	84 ~~212~~	250 ~~240~~	345 ~~269~~

TABLE 5.2

Comparison of Rules Arcus, P, Q, R, X, Y and Z

TV Main Chassis Problem

Number of work elements = 97 Cycle time = 6.5 minutes

Rule	Arcus	P	Q	R	X	Y	Z
11 Stations	346	432	395	320	457	371	321
12 Stations	654	568	605	680	543	629	679
Station Mean	11.654	11.568	11.605	11.68	11.543	11.629	11.679
Operation Mean	9.133	9.038	9.200	9.118	9.062	9.023	9.13
Total Execution time in seconds	702	698	705	705	697	706	705
Expected time for optimal solution in seconds	2.03	1.62	1.78	2.20	1.53	1.91	1.10
First optimal sequence number	6	1	1	1	1	1	1

TABLE 5.3

Comparison of Rules Arcus, P, Q, R, X, Y and Z

Refrigerator Final Assembly

Number of work elements = 96 Cycle time = 154 seconds.

Rule	Arcus	P	Q	R	X	Y	Z
23 Stations	69	189	283	78	170	262	49
24 Stations	667	696	647	668	698	659	647
25 Stations	263	114	70	254	132	79	304
Station Mean	24.196	23.927	23.787	24.176	23.962	23.817	24.255
Operation Mean	4.708	4.676	4.821	4.728	4.669	4.620	4.735
Total Execution time in seconds	401	404	397	400	403	400	405
Expected time for optimal solution in seconds	5.82	2.14	1.4	5.12	2.37	1.53	8.25
First optimal sequence number	10	5	8	8	5	5	13

TABLE 5.4

Comparison of Rules Arcus, P, Q, R, X, Y and Z

Truck Assembly Problem

Number of work elements=111 Cycle time = 68 seconds

Rule	Arcus	P	Q	R	X	Y	Z
27 Stations	5	?	12	1	1	3	2
28 Stations	964	902	976	953	893	983	960
29 Stations	31	96	12	40	105	14	38
30 Stations	0	2	0	0	1	0	0
Station Mean	28.026	28.100	28.000	28.039	28.106	28.011	28.036
Operation Mean	9.725	8.077	9.730	9.721	8.061	9.714	9.702
Total Execution time in seconds	749	658	754	750	654	760	758
Expected time for optimal solution in seconds	150	?	63	750	654	253	379
First optimal sequence number	219	?	12	121	872	463	313

Table 5.4 contains the results of truck assembly problem. The results reveal that rule Q is the best out of all the rules tried. It is interesting to note that rule P which turned out to be the best with assembling clothes problem and T.V. chassis assembly problem could not generate at least one optimal solution to the truck assembly problem.

In order to have a better confidence in concluding the effectiveness of the weighting procedures tests were conducted to prove the effectiveness of the rule Q. The test results are presented in the next section.

5.5.2 Testing The Effectiveness of Rule Q

For generating the sequences by the computer a built in function called RNDY1 is used. RNDY1 uses a seed of 189277. It generates random numbers which lie between 0 and less than 1. The inference that rule Q fairs better than other rules is not with much basis because all the above results are based on only one random number. In order to have a better level of confidence it is necessary that tests are conducted using more than one random number. The four other random number generators available with the IBM 7044 system at I.I.T. Kanpur are RNDY2, RNDY3, RNDY4 and RNDY5. The seeds for these functions are 186285, 186293, 186301 and 186309 respectively. Results obtained for the four test problems using the above 5 seeds are presented in Table 5.5. The top value in each cell corresponds to rule Q and the bottom value corresponds to rule Arcus.

A non parametric sign test is conducted to test the hypothesis that the weighting procedure by rule Q is better than rule Arcus. Let α_i and β_i denote mean number of work station for rules Q and Arcus respectively using seed i.

Then

$$H_N : \alpha_i > \beta_i$$

and H_A : H_N is false

Table 5.5

Comparison of Rule Q with Rule Arcus for Different Seeds

Seed / Problem	45 Element Problem	97 Element Problem	96 Element Problem	111 Element Problem
RNDY1 189277	3.991 3.992	11.605 11.654	23.787 24.196	28.000 28.026
RNDY2 186285	3.991 3.998	11.616 11.662	23.940 24.179	28.009 28.026
RNDY3 186293	3.983 3.992	11.624 11.664	23.915 24.181	28.011 28.032
RNDY4 186301	3.984 3.993	11.610 11.671	23.947 24.187	28.015 28.026
RNDY5 186309	3.989 3.990	11.634 11.679	23.932 24.214	28.003 28.036

We have five paired observations, with the first observation in the pair coming from population one which uses rule Q and the second observation from population 2 which uses rule Arcus. A plus sign is used to replace each pair for

for which the observation from the 2nd population exceed that of the first population. A minus sign is used to replace each pair for which the observation from the first population exceeds that from the second population.

For the sample size of five for which the rules are tested, all plus signs are obtained for all the four problems. Using the normal curve approximation and $\alpha = 0.05$ we calculate

$$Z = \frac{x - np_o}{\sqrt{np_o (1 - p_o)}}$$

where

x is number of successes

n is the sample size

p_o is the probability of getting a success.

Thus for our problem

$$Z = \frac{5 - 5 \times 0.5}{\sqrt{5 \times 0.5 (1 - 0.5)}} = 2.22$$

This exceeds 2.015, the critical value for a one sided test at the 0.05 level of significance and so we conclude that the null hypothesis must be rejected. In other words, we conclude that the biasing using rule C produces better results than the biasing by rule Arcus.

The balances obtained for the four problems using rule C are presented in Tables 5.6 to 5.9.

TABLE 5.6

Optimal Allotment of Work Elements to Work Stations
For the Assembling Clothes Problem

Number of work elements = 45 Cycle time = 207.8 secs.

Total work content = 622.46 sec. Line Idle time = 0.94 sec.

Station Reliability = 99.85% Line reliability = 99.59%

Station No.	Elements alloted to the station	Station Mean sec.	Station Variance $(sec.)^2$	Station time sec.
1	1,2,3,4,5,7,8,9,11,12,13,14,15,16, 18,34	188.0	43.5	207.63
2	17,19,20,21,23,24,25,27,30,32	174.0	121.0	206.95
3	6,10,22,26,28,29,31,33,35,36,37, 38,39,40,41,42,43,44,45	190.0	34.81	207.75

TABLE 5.7

Optimal Allotment of Work Elements to Work Stations
For the EC TV - Main Chassis Problem

Number of work elements = 97 Cycle time = 6.50 min.

Total work content = 70.53 min Line idle time = 0.97 min.

Station Reliability = 99.85% Line reliability = 98.60%

Station No.	Elements alloted to the station	Station Mean min.	Station Variance $(min.)^2$	Station time min.
1	1,7,8,11,22,23,27	5.63	0.069	6.42
2	2,3,4,5,12,21,24,25,28,29	5.34	0.141	6.47
3	6,13,15,16,18,19,26,37	5.33	0.149	6.49
4	9,10,14,17,20,30,31,32,33,34,35, 36,38,39,69	5.43	0.111	6.43
5	40,41,42,43,44,57	5.68	0.075	6.50
6	46,60,71,72,86,90	5.13	0.146	6.48
7	45,47,61,68,91,92	5.55	0.096	6.48
8	54,55,58,73,74,81,93,94	5.58	0.069	6.37
9	48,59,62,75,76,87,88,95,96	5.02	0.205	6.38
10	49,50,51,56,63,64,65,66,77,79,80,82	5.87	0.036	6.45
11	52,53,67,70,78,82,83,84,85,89,97	5.21	0.081	6.06

TABLE 5.8

Optimal Allotment of Work Elements to Work Stations For the Refrigerator Final Assembly Problem

Number of Work Elements = 96 Cycle time = 154.00 secs.

Total work content = 3364.29 secs. Line idle time = 177.71

Station reliability = 99.85% Line reliability = 96.87%

Station No.	Element Alloted to this station	Station Mean sec.	Station Variance $(sec.)^2$	Station time sec.
1	1,4,5,6	120.20	111.0	151.84
2	7,8,11,14,15,16,	107.10	170.0	146.32
3	9,10,12	123.70	92.0	152.49
4	2,3,13,17,18,19,37	127.90	74.5	153.82
5	20,21,22	118.10	85.0	145.78
6	23,24,25	127.00	24.0	141.35
7	26,27,28,35	127.70	75.5	153.79
8	29,30	112.80	56.8	135.42
9	31,47,48	120.13	68.5	144.96
10	38,39,49,50,51	119.90	52.0	141.54
11	32,34,40,41,42	122.00	58.0	144.89
12	43,44,45,46	111.00	83.8	138.45
13	52,53,54,60	130.90	50.8	152.25
14	61,62,63,64	122.30	43.0	141.94
15	33,55,65,66,72,90	127.20	46.25	147.50
16	67,68,69,70,71,73,74,91,92	126.90	72.0	152.37
17	56,75,76,77,78,79,80,81,93	127.50	57.8	148.00
18	82,83,94	133.20	44.9	153.28
19	84,85	130.20	53.0	152.04
20	86,95	115.17	44.0	135.08
21	87, 96	130.50	44.0	150.46
22	57,58,88,89	132.40	33.0	149.66
23	36,59,88	109.47	57.8	131.05

TABLE 5.9

Optimal Allotment of Work Elements to Work Stations For the Truck Assembly Problem

Number of Work Elements = 111

Total work content = 1791.26 sec.

Station Reliability = 99.85%

Cycle time = 68.0 secs.

Line idle time = 44.74 secs.

Line reliability = 96.34%

Station No.	Elements alloted to this station	Station Mean. sec.	Station variance (sec.)^2	Station time sec.
1	1,2,3,101	49.00	5.30	55.91
2	4,10,11	57.49	10.00	67.95
3	7,8,12,14,16,19,24,30	62.87	2.65	67.75
4	9,13,17,20,23	58.83	9.25	67.95
5	21, 25	64.90	0.98	67.87
6	6,27,28,34,38	56.82	10.34	67.80
7	22,36,42	58.76	9.50	67.98
8	47,55	53.25	23.80	67.91
9	5,18,29,35,37,43,44,45,46,48,49, 51,52,53,56	51.53	30.00	67.94
10	60.62	59.78	7.45	67.93
11	32,50,61,68	50.94	26.20	66.32
12	41,54	46.78	45.00	66.91
13	57,69,71	52.49	21.20	66.33
14	70,73	55.92	5.88	63.19
15	58,64,65,75	60.29	2.40	64.94
16	59,72,78	57.08	7.90	65.52
17	74,77,79	46.76	26.20	62.19
18	76,77,79	54.88	18.80	67.86
19	81,84,85	53.22	39.90	64.40
20	15,80,87	49.55	26.50	64.99
21	90,91,92,93,94	63.88	0.86	66.66
22	86,88,95	60.39	4.20	66.54
23	31,63,98,103,108	55.92	15.80	67.81
24	39	49.98	34.00	67.46
25	26,40,97,99	58.69	6.60	66.39
26	83,66,82,96,100,102,106	61.99	3.75	67.80
27	67,89,104,105,107,109,110,111	53.00	24.70	67.91

5.5.3 Comparison with Moodie and Young (24) Algorithm

The only other method which accounts for variability in ALB problem is the one proposed by Moodie and Young. It was thought that a comparison of the proposed methodology with that of Moodie and Young would be a worthwhile effort. In the following sections a comparison between the two approaches is presented.

The T.V Main Chassis assembly problem and the Refrigerator final assembly problem are tested for the purpose. For the T.V Main Chassis assembly problem, a cycle time of 6.5 minutes is used. In the Moodie and Young's procedure the cycle time is automatically incremented if the line idle time exceeds the cycle time. The final output cycle time of this model turned out to be 7.36 minutes. Similarly for the Refrigerator problem, though a cycle time of 164 seconds is inputted, the final output cycle time turned out to be 200.9 seconds. Both the output cycle times when used for respective industries do not meet the management production requirements. This is considered to be a major drawback of the Moodie and Young's method and therefore the practical utility of such a methodology is very much reduced.

For the sake of comparison of the two methodologies the input cycle time for the proposed methodology is altered to 7.36 min. and 200.9 sec. for TV and Refrigerator problems. As is the case in the Moodie and Young's methodology, the

TV problem required 10 work stations and the Refrigerator problem 17 work stations. But there is considerable improvement in respect to the computation time. As against 22 seconds of execution time for TV problem using Moodie and Youngs procedure, the proposed methodology required only 0.7 secs. for the generation of a solution requiring 10 stations. It is found that there is a similar improvement with respect to the Refrigerator problem, Moodie and Youngs procedure took 14 secs. as compared to 0.4 secs. for the proposed methodology.

Thus it is concluded that the present methodology generates solutions which not only meet the management production requirements but also reduces the computation time involved.

5.5.4 Sensitivity Analysis

The management may be interested in knowing the sensitivity of the balance with respect to the reliability of the line. With this in view the TV and Refrigerator problems are tested for various degrees of confidence. Throughout the test the cycle time is kept constant and the value of the cycle time is assumed to be prescribed by the management to meet the production requirements. The input cycle times for the TV and the Refrigerator problems are 6.5 min. and 164 secs. respectively. Table 5.10 gives the results for both the TV and Refrigerator problems. The top value in each cell corresponds

to the number of work stations and the lower value corresponds to the corresponding idle time.

TABLE 5.10

Number of Work Stations required for various degrees of confidence.

Confidence level at work station	Number of work stations	
	TV Problem	Refrigerator problem
r = 0.0 50%	10 / 5.35	20 / 256.73
r = 0.5 69.15%	10 / 3.63	20 / 172.66
r = 1.0 84.13%	10 / 1.87	21 / 238.43
r = 1.5 93.32%	11 / 6.55	21 / 151.46
r = 2.0 97.73%	11 / 3.63	22 / 212.18
r = 2.5 99.38%	11 / 2.77	23 / 270.01
r = 3.0 99.86%	11 / 0.95	23 / 178.12

It is observed that the number of work stations increase as the level of confidence increases. An analysis of this type provides the management an option to operate each work station at any desired level of confidence.

In this chapter a m thodology which successfully solves the variability in work element times problem, has been presented. In the next chapter, an attempt is made to propose a methodology for taking care of the variability in work element times and variability in operator performance.

CHAPTER 6

APPROACH TO BALANCING ASSEMBLY LINES WITH PROBABILISTIC WORK ELEMENT TIMES AND VARIABLE OPERATOR PERFORMANCE LEVELS

6.1 Introduction

In chapter 5, it has been pointed out that besides probabilistic work element times, variable operator performance level is an important factor for consideration in industrial assembly lines. The problem of line balancing with variable performance level is different because in this case the cycle time for each operator is different. This problem cannot be handled by using the methodology presented in chapters 4 and 5. Therefore, in this chapter a methodology which jointly takes care of probabilistic times and variable operator performance is presented. A few practical considerations which form input to the methodology are discussed before presenting the details of the methodology.

6.2 Practical Consideration

The estimation of both the average work performance level of operators and work element times involve human judgement and therefore normally have large errors. The presence of large amount of errors in these estimates have been reported by Barnes (2). The errors involved in estimating the variables makes one doubt the usefulness of line balancing techniques to industrial assembly lines. For example, a suitable set of work units whose cumulative time is slightly

greater than the cycle time cannot be assigned to the work station. The excess time may be of no practical consequence. The question would then arise as to what should be the magnitude of the allowable excess time. The allowable excess time is a function of the magnitude of errors involved in estimating the variables. A five percent error in the estimation of operator's rating is the target generally aimed at in most training courses on performance rating. Rarely do time study analysts achieve this target. Studies of experienced time study analysts have indicated that the time study errors far exceed 5%. Thus it becomes necessary to reflect these errors in balancing techniques for better results.

6.3 Concepts for the Methodology

6.3.1 Loading the Operators

The process of alloting work to the operators is termed as the maximum loading of stations. The procedure consists of the selection of suitable operator for a station. The suitability of the operator for a particular station is judged from the idle time he creates due to his allotment to this work station. The operator who results in the least amount of idle time for a station is alloted to that station before passing on to the next station. This procedure is repeated till each station gets an operator.

The total number of workers on the line are divided into a number of labour pools. A labour pool consists of

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The total number of workers on the line are divided into a number of labour pools. A labour pool consists of

operator with equal performance rating. Every operator from a particular labour pool gets the same amount of work as the other operators in the same labour pool. The work load allotted to each station is less than or equal to the product of the cycle time and the rating of the operator.

6.3.2 Selection of Work Elements

For each operator the elements are selected by a biasing procedure. Rule Q, which was found to be the best biasing procedure in Chapter 5 is also made use of for the selection of work elements. The number of sequences that are tried for each operator is based on the following three devices.

(i) A test is made to check if a sequence for an operator has an idle time ratio equal to or less than an acceptable amount. The acceptable idle time at each station is a management decision variable. As the acceptable idle time reduces more number of sequences are to be tried which in turn increases the computational time.

(ii) A maximum limit is placed on the number of sequences tried at each station for all the operators. It may be raised or lowered in the light of experience and available computer running time.

(iii) To limit the number of sequences tried at a station, a method of counting the feasible sequences is proposed.

At the time of each selection, the product Z of number of work elements in the fit list is computed. The product Z for the first sequence is taken as the number of sequences to be tried unless (a) a subsequent sequence has a larger Z, (b) it exceeds the maximum limit of sequences to be tried or (c) a sequence has an acceptable idle time ratio.

6.3.3 Operator Selection :

Two approaches for the selection of operators for the various stations are proposed. In the first approach all the operators available for allotment to a work station are tried. The operator who yields least idle time for the work station is selected. One of the most important features of this approach is that only after judging the suitability of all the operators the one who creates the least idle time is selected. In the second approach operators available for allotment to a work station are tried randomly. If an operator results in an idle time less than or equal to the allowable idle time, the operator is selected. The other available operators are not tried. Results obtained by using these approaches are presented in this chapter.

6.3.4 Objective

In this methodology the objective is to minimize the cycle time for a given number of operators. The input cycle time is taken to be an arbitrary value usually governed

While generating a sequence, if all the available operators get alloted leaving a few unassigned work elements, the assigning procedure is repeated till the "assignment limit" for a particular cycle time is reached. Only after reaching the assignment limit, the cycle time is incremented and a new balance is tried.

If the number of operators are sufficient and the line idle time is less than the number of work stations multiplied by minimum time unit, an optimal solution is obtained. However, if the operators are sufficient but the line idle time is greater than number of work stations multiplied by minimum time unit, the cycle time is decremented and the assignment procedure repeated.

The number of assignments to be tried for a cycle time is an input variable and depends on the management depending on the available computation time.

6.4 Solution Procedure

The following is the step by step procedure for obtaining the solution. A logical flow chart for the procedure is presented in Fig. 6.1.

Step 1 : Calculate the average performance time of the given labour pool and the line cycle time.

Step 2 : Create a master list of work elements with preceding operations.

Step 3 : Transfer Master list to working list.

Step 4 : Select an operation and calculate the acceptable work load for the operation with % allowance for estimating errors.

Step 5 : From the working list identify elements with zero precedents and transfer them into the "Availability List".

Step 6 : Transfer the available operations into the "Fit List" if the following condition is satisfied.

$$\sum_{i \in k} E_i + E_j + r\sqrt{\sum_{i \in k} V_i + V_j} \leq W_k + W_k^*$$

where i elements have been already alloted to k^{th} operation and W_k^* is the allowance for estimation error. The j^{th} element is the element under consideration for fitting into this station.

If this is the first element to be alloted to the station, then $\sum E_i = 0$ and $\sum V_i = 0$.

If none of the available elements fit, then go to step 10, otherwise go to step 7.

Step 7 : Weight tasks in the "Fit list" using rule Q. Generate a random number and identify operation that is to be selected. Store work element and operation number. Update the station time to

$$\sum_{i \in k} E_i = \sum_{i \in k} E_i + E_j$$

$$\sum_{i \in k} V_j = \sum_{i \in k} V_j + V_i$$

Step 8 : If this is the N^{th} task go to step 11, otherwise go to step 9.

Step 9 : Change the number of preceding work elements in the working list and go to step 5.

Step 10: Compute product Z and compare with No. of sequences generated. If generated sequences are less than product Z then go to step 11. If generated sequences are equal to product Z then go to step 13.

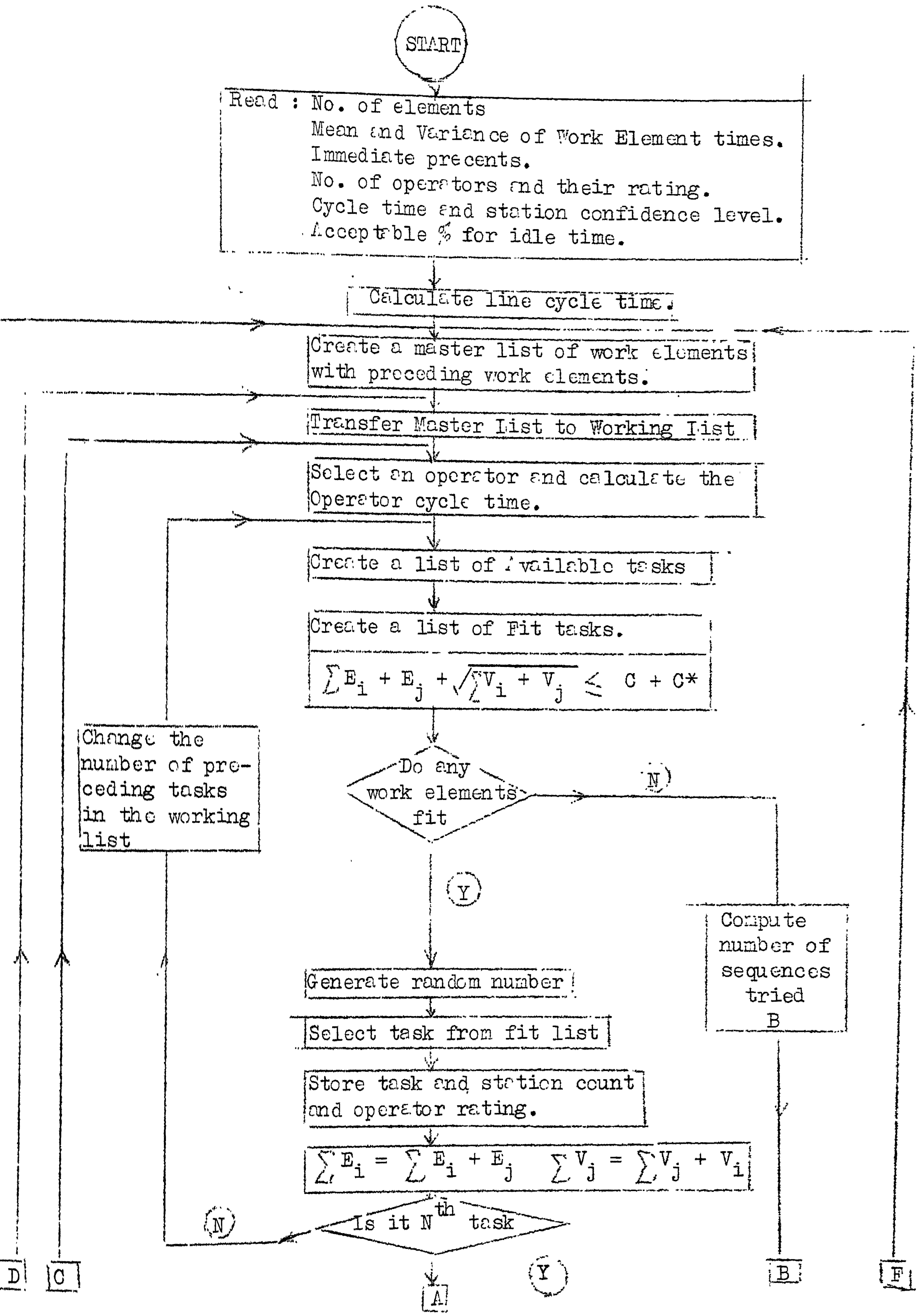
Step 11: If the idle time for the operator is within the acceptable limit (W_j*) go to step 12 otherwise update working list by dropping selected work elements and go to 4.

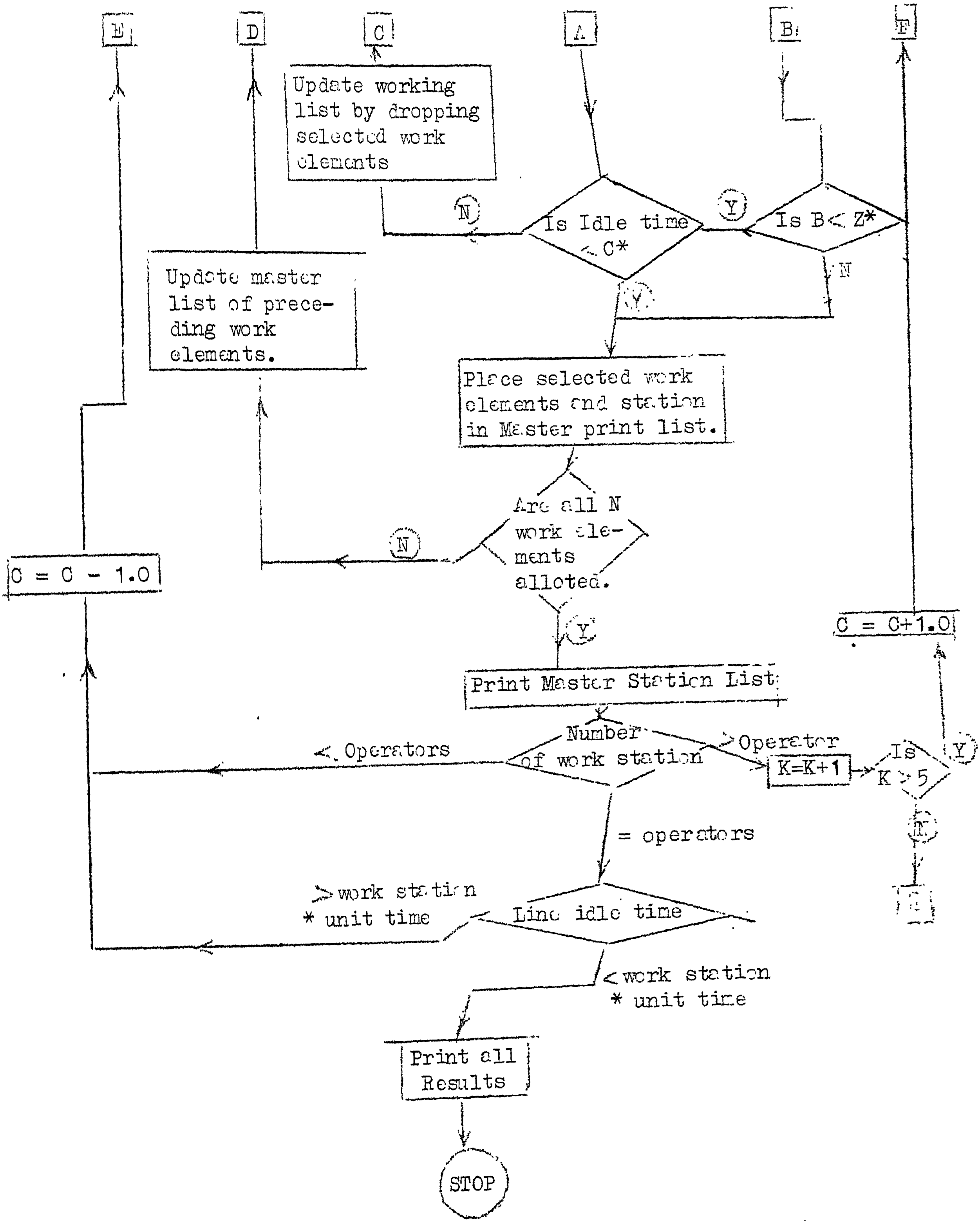
Step 12: Place selected work elements and station operator into the Master Print list. Update the Master Print list by including the selected work elements and station operator.

Step 13: If all the work elements have been alloted, go to Step 1. Otherwise update master list of preceding work elements and go to step 3.

Step 14: Print Master Station List. If the number of station equals given operators go to step 15. If less than given operator decrement cycle time and go to step 2. If greater than given operator increment cycle time and go to step 3.

Fig. 6.1 Logical Flow Chart For Loading Stations Maximally.




E
D
C
A
B
F
Update working list by dropping selected work elements
N
Is Idle time < C*
Y
Is B< Z*
N
Y
Update master list of preceding work elements.
Place selected work elements and station in Master print list.
N
Are all N work elements alloted.
Y
C = C - 1.0
C = C+1.0
Print Master Station List
< Operators
Number of work station
> Operator
K=K+1
Is K > 5
Y
N
= operators
> work station * unit time
Line idle time
< work station * unit time
Print all Results
STOP

Step 15 : If line idle time is less than work stations * unit time go to step 16. If the idle time is greater than work stations multiplied by unit time, decrement cycle time and go to step 2.

Step 16 : Print all results.

6.5 Results and Discussions

To test the methodology a computer package written in FORTRAN IV for IBM 7044 system has been developed. The computer package named CALBPROP - II (acronym for Computerized Assembly Line Balancing with Two Probabilistic Parameters) can handle upto 120 element problem and consumes about 16 K of computer memory. The listing of the programme is given in Appendix G.

The T.V. problem and the refrigerator problem are the two problems tested to validate this methodology. The assembling clothes problem and truck assembly problem are not tested since for them there is no data available on operator performance level. The available operators and their corresponding performance ratings for the two problems tested are given in Appendix B and C.

The inputs to the programme are

(i) Work elements and their precedents.

(ii) Element times and element time variances.

(iii) Level of confidence desired at each work station.

(iv) Labour pools and their performance rating.

(v) Allowance for errors in estimating the parameters

(vi) Allowable idle time ratio.

(vii) Maximum number of sequences to be tried at each work station and

(viii) Maximum number of assignments for a given cycle time.

The output of the package includes

(i) Operator selected at each work station.

(ii) Allowable work load for the selected operator.

(iii) Alloted work elements and the corresponding work content at each station.

(iv) Number of sequences tried for each work station.

The package can handle the random selection as well as sequential selection of operators.

An input cycle time of 6.5 minutes and the random selection of operators gives an output cycle time of 6.68 minutes for the T.V. problem. For the same input cycle time the procedure of selecting the operators sequentially gives an output cycle time of 6.58 minutes.

The refrigerator problem when tested with an input cycle time of 154 sec. and random selection of operators gives an output cycle time of 154 sec. For the same input cycle time, the procedure of selecting the operators sequentially results in an output cycle time of 151 sec. In all the above

cases, the allowance for error in estimating the parameters is 5% of the cycle time, the acceptable idle time ratio is 5% of the cycle time, the maximum number of sequences generated at each station is 100 and the assignment limit for each cycle time is 5.

It can be concluded from the above results that loading stations maximally by selecting the operators sequentially gives better results than selecting the operators randomly.

The detailed results obtained by loading stations maximally by the sequential selection of operators are presented in Tables 6.1 and 6.2. The solutions obtained for the T.V. and Refrigerator problem are tabulated in Tables 6.1 and 6.2 respectively. It is interesting to note that for the T.V. problem the operators are selected in the ascending order of their performance rating whereas for the refrigerator problem no such tendency is observed. It can also be noted that at most of the work stations the 5% allowance for the errors involved in estimating the parameters is fully utilised.

To have an insight into the behaviour of the assembly line system with variations in the allowance for the errors in estimating parameters a 2% allowance was also tried. For the sequential selection of operators the T.V.

problem and Refrigerator problem resulted in cycle times of 6.68 minutes and 153 seconds respectively. This definitely indicates that as the allowances for estimation errors is reduced, the cycle time is increased.

TABLE 6.1

Solution to TV Problem when Operators are loaded maximally.

Line Cycle time = 6.58 mins. Computation time = 3 secs.

Work Station No.	Rating of selected operator	Allowable work load for operator	Alloted work load for operator	Elements alloted to the operator
	%	Minute	Minute	
1	85.0	5.59	5.68	1,2,7,21,22,23,28
2	90.0	5.92	6.08	3,4,8,24,25,26,27,29
3	95.0	6.25	6.51	5,6,9,11,12,13,18,37,38
4	95.0	6.25	6.50	10,14,15,16,17,19,20,30,31,32, 33,34,35,39
5	95.0	6.25	6.36	36,40,41,42,43,54
6	95.0	6.25	6.50	44,46,60,90,91
7	95.0	6.25	6.41	55,57,58,61,71,80,81,92,93
8	95.0	6.25	6.39	56,62,72,73,74,75,83,86,94
9	100.0	6.58	6.89	47.48, 49,68,87,95,96,97
10	100.0	6.58	6.75	45,59,63,64,66,65,70,76,79,82
11	110.0	7.23	6.41	50,51,52,53,67,69,77,78,84,85 88,89

TABLE 6.2

Solution to Refrigerator Problem when Operators are loaded maximally.

Line Cycle Time = 151 secs. Computation time = 24 secs.

Work Station No.	Rating of selected operator %	Allowable work load for operator seconds	Alloted work load for operator seconds	Elements alloted to the operator
1	80.0	120.80	124.62	2,3,6,7,37
2	85.0	128.35	130.97	1,5,8,14
3	85.0	128.35	130.90	9,11,15,16,17
4	95.0	143.45	144.05	4,10,12
5	105.0	158.55	166.43	13,19,20,21
6	95.0	143.45	150.24	18,22,23,24
7	90.0	135.90	140.04	25,26,27,35
8	90.0	135.90	137.98	28, 29
9	90.0	135.90	131.48	30,38,39
10	90.0	135.90	140.76	31, 47
11	95.0	143.45	141.59	32,40,41,42,48,49
12	95.0	143.45	146.50	43,44,50
13	95.0	143.45	145.15	33,45,46,51,52,60
14	95.0	143.45	144.47	53,54,55,56
15	95.0	143.45	150.54	61,62,63,64,65
16	95.0	143.45	147.13	34,66,67,70,71,72,73
17	100.0	151.00	153.47	68,69,74,75,76,77,90,91,92,93
18	100.0	151.00	153.87	78,79,80,94
19	100.0	151.00	144.21	36,81,95
20	110.0	166.00	171.19	57,82,83,84
21	105.0	158.55	157.65	58,59,85,86
22	105.0	158.55	150.46	87,96
23	105.0	158.55	163.46	88,89

CHAPTER 7

SCOPE FOR FURTHER RESEARCH

In this dissertation, a few methodologies were developed to provide solutions efficiently for single model industrial assembly lines. However, there are some aspects of ALB problems which need attention of the researchers. Some of the potential avenues for further research are given below.

So far no attempt has been made to develop methodologies for handling multi-model assembly lines considering probabilistic parameters. The author feels that the methodologies proposed in this dissertation, with a few modifications, could provide an answer to this complex problem. However, a study needs to be undertaken to justify this claim.

Graph theory concepts are extremely useful for handling combinatorial problems. One of the important and taxing features of ALB problem is its high combinatorial nature. Therefore, application of graph theory concepts to ALB problems seems to have good potential.

In the operator assignment procedure presented in this thesis, by loading each operator maximally a local optimum is being sought. The best operator for a work station is selected without trying the operator for other work stations. Instead, by checking the suitability of each operator for all the work stations and then alloting the operators by an "assignment procedure" with a view to minimize the total idle time on the line might yield a a global optimal solution. Though this may need high computational time yet it may be a field worth exploring.

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APENDIX -A

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ASSEMBLING CLOTHES PROBLEM - DATA

TABLE A-1

DATA ON WORK ELEMENTS

T	DESCRIPTION	MEAN TIME (SEC)	VARIANC (SEC)
	PICK UP AND PUT ON LEFT SOCK	9	1.971
	PICK UP AND PUT ON RIGHT SOCK	9	0.093
	PICK UP AND PUT ON LEFT SHOE	10	3.097
	PICK UP AND PUT ON RIGHT SHOE	10	1.849
	TIE LEFT SHOE LACE	17	3.370
	TIE RIGHT SHOE LACE	17	0.004
	PICK UP, PUT ON, AND ATTACH LEFT GARTER	13	4.999
	PICK UP, PUT ON, AND ATTACH RIGHT GARTER	13	1.690
	PI+K UP, PUT ON LEFT SPAT	20	9.000
	PICK UP, PUT ON RIGHT SPAT	20	11.289
	PICK UP AND PUT ON UNDERSHORTS	10	0.000
	PICK UP AND PUT ON UNDERSHIRT	11	0.627
	TUCK IN UNDERSHIRT	6	0.8317
	PICK UP AND PUT ON TROUSERS	22	8.233
	PICK UP AND PUT ON SHIRT	11	3.020
	BUTTON 5 BUTTCNS	19	3.755
	TUCK IN SHIRT	12	4.665
	TURN UP COLLAR	3	0.046
	PICK UP AND PLT ON TIE, TURN COWN COLLAR	7	0.433

BUTTON SHIRT NECK BU‡TTN	4	0.2621
TIE TIE	55	74.6529
PICK UP AND PUT ON TIE CLIP	14	0.6499
FOLD BACK LEFT CUFF-PICK UP AND PUT ON LEF, CUFF LINK	27	10.4976
FOLD BACK RIGHT CUFF-PICK UP AND PUT ON RIGHT CUFF LINK	29	27.8573
PICK UP AND PUT ON BELT	26	0.2704
BUCKLE BEL‡	6	0.5535
PICK UP AND PUT ON VEST	5	0.9801
BUTTON VEST(6 BUTTONS)	24	8.0202
PICK UP AND PLACE HANDKERCHIEF	4	1.3540
PICK UP PLACE VALLE‡	5	0.5329
PICK UP AND PLACE SMALL CHANGE	7	0.4516
PICK UP AND PLACE KEYS	4	0.4844
PICK JP AND PUT ON SUIT JACKE‡	15	2.3409
PICK UP AND PUT ON WRIST WATCH	5	0.5776
PICK UP AND PLACE POCKET HANDKERCHIEF	7	0.4706
PICK UP AND PLACE FOUNTAIN PEN	9	1.5420
PICK JP AND PLACE GLASSES	4	0.5300
PICK UP AND PLACE GLASS CASE	3	0.2421
BUTTON SUIT JACKE‡	7	0.7056
PICK UP AND PUT ON SCARF	4	0.5069
PICK UP AND PUT ON TIP COAT	21	1.3830
BUTTON TOP COAT	12	4.9818
PICK UP AND PUT ON LEF‡ GLOVE	5	0.3136
PICK UP AND PUT ON RIGHT GLOVE	5	0.0169
TOTAL WORK CONTENT	552	

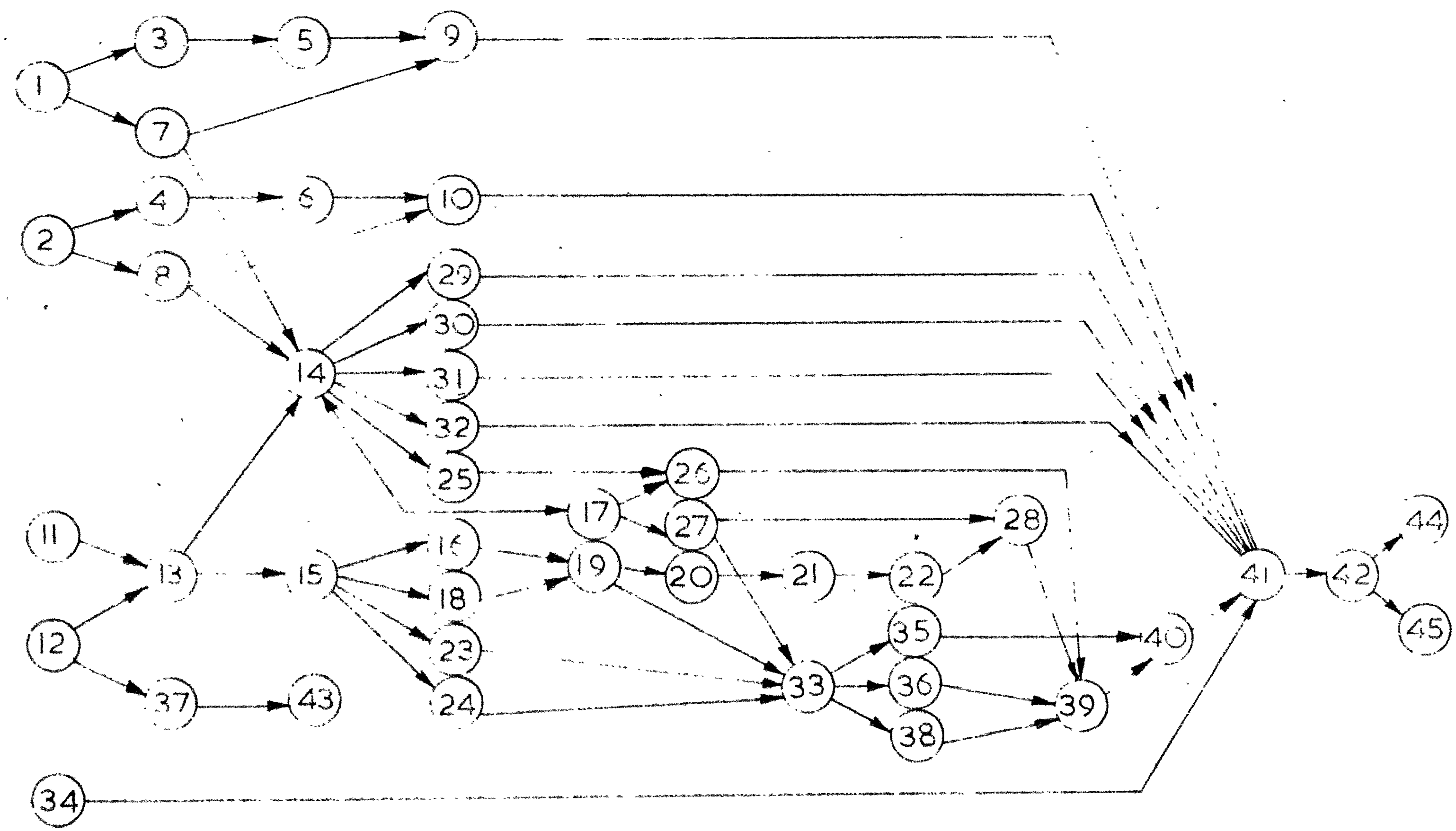

FIG. A1 PRECEDENCE GRAPH- ASSEMBLING CLOTHES

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APENDIX -B

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TV MAIN CHASSIS PROBLEM - DATA
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TABLE B-1

DATA ON WORK ELEMENTS

DESCRIPTION OF THE WORK ELEMENT	MEAN TIME (MIN)	VARIANCE (MIN)**2
PICK UP BOARD AND KEEP IT ON LINE,PICK UP CHASSIS AND KEEP IT ON THE BOARD	0.19	0.0009
CUT ALL THE TIPS FOR THE SOCKET WIRE	0.30	0.0105
BEND WIRES,PICK UP SOCKE, AND FIX IT	1.32	0.0290
SOLDER ALL POINTS ON THE SOCKET	0.76	0.0413
FIX CAPACITOR ON SOCKET WIRES AND SOLDER	0.43	0.0037
CUT TIPS	0.46	0.0128
BEND AND FIX WIRES TO LO‡	1.71	0.0212
SOLDER NINE POINTS ON LOT	0.71	0.0141
CONNECT TWO WIRES TO EARTH LUG AND SOLDER	0.26	0.0028
BEND THE WIRES AND PUT THE STAMP	0.30	0.0035
CUT ALL ENDS OF WIRE	0.82	0.0080
FIX ONE BLACK WIRE TO EARTH LUG AND SOLDER	0.24	0.0044
BEND ENDS OF FOUR WIRES AND FIX TO SK3	0.72	0.0272
SOLDER ABOVE FOUR WIRES ON SK3	0.22	0.0023
FIX SHIELD WIRE ON SK3 AND SOLDER	0.44	0.0070
BEND ENDS OF THREE WIRES AND FIX TO SK1	0.53	0.0282
SOLDER SK1	0.24	0.0149
BEND ENDS OF EIGHT WIRES AND FIX TO SK2	0.50	0.0104
PRESS THE WIRES	0.24	0.0069
INSERT SLEEVES ON FOUR TRANSISTOR TERMINALS	0.38	0.0231
PICK UP WIRE BUNCH, FIX THREE WIRES ON SK3 AND SOLDER	1.17	0.0204
FIX TWO WIRES TO EARTH LUG AND PINK WIRE TO CHOKE AND SOLDER	0.70	0.0007
FIX FOUR WIRES TO RIGHT TRANSISTOR	0.82	0.0217

FIX FIVE WIRES TO LEFT TRANSISTOR	0.49	0.0036
SOLDER ALL NINE WIRE-POINTS	0.41	0.0006
FIX TWO WIRES TO EARTH LUG AND SOLDER	0.33	0.0033
TWIST TWO WIRES AND PUT SLEEVE ON TRANSISTOR	0.36	0.0065
TINNING OF THE WIFES	0.22	0.0029
PICK UP HARNESS TWO AND FIX WIRE ON SK3	0.49	0.0074
FIX SHIELD WIRE TO EARTH LUG ANDONE WIRE ON SK1	0.28	0.0023
SOLDER BOTH POINTS	0.18	0.0038
FIX SIX WIRES ON SK2	0.85	0.0328
SOLDER ALL POINTS	0.26	0.0045
FIX TWO SHIELD WIRES, A BLACK WIRE AND SOLDER	0.58	0.0041
TAG WIRE BUNCH AT TWO POINTS	0.71	0.0204
FIX BLACK WIRE TO EARTH LUG, TWO WIRES TO TRANSISTOR AND ONE RESISTOR TO EARTH	0.68	0.0134
PICK UP PINK WIRE ,FIX ONE END ON TRANSISTOR AND THE OTHER ON CHOKE	0.26	0.0013
SOLDER ALL POINTS (FIVE NOS.)	0.31	0.0027
PICK UP EHY, PLACE IT ON MAIN CHASIS,FIX FOUR BOLTS AND NUTS	1.57	0.0092
PICK UP CONDENSOR, PLACE IT ON MAIN CHASIS AND FIX TWO SCREWS	0.99	0.0043
PICK UP TRANSFORMER, FIX IT ON MAIN CHASIS WITH ONE SCREW LOOSE	1.30	0.0050
MEASURE LENGTHS	0.65	0.0181
TIGHTEN FOUR SCREWS OF TRANSFORMER	0.59	0.0346
FIX FOUR DIODES AND SOLDER	1.31	0.0098
TIN TWO WIRES	0.26	0.0040
POINTS ON THE TRANSFORMER	1.02	0.0240
PICK UP TWO MORE WIRES, FIX AND SOLDER	0.47	0.0073
FIX ONE GREY WIRE AND A BLACK WIRE AND SOLDER	0.41	0.0042
TWIST TWO BROWN WIRES, FIX AND SOLDER THEM ONTO THE CAP	0.32	0.0020
FIX TWO BLUE WIRES AND ONE VIOLET WIRE AND SOLDER	0.58	0.0019
TWIST ONE BLACK WIRE, FIX IT AND SOLDER	0.76	0.0049
FIX ONE CAPACITOR AND SOLDER	0.47	0.0035
FIX TWO WIRES ON CHOKE	0.40	0.0038
PICK UP TUNER BUNCH AND FIX FOUR WIRES ON SK1 ,AND TWO ON EARTH LUGS	1.01	0.0037
SOLDER ON SK1 AND EARTH LUGS	0.36	0.0029
ICK UP YELLOW BUNCH AND FIX THREE WIRES ON SK1	0.58	0.0035
OLDER THE ABOVE POINTS	0.04	0.0028
YE TUNER AND YELLOW BUNCH	0.62	0.0054
IX THREE WIRES OF MAIN CABLE ON TRANSFORMER D FIX TWO WIRES ON FUSE HOLDER	0.95	0.0084
LDER THE ABOVE POINTS	0.21	0.0010
K BLUE BUNCH AND FIX THREE WIRES ON THE NSFORMER	0.57	0.0004
LDER ABOVE THREE POINTS	0.23	0.0022
-UP BLUE BUNCH	0.39	0.0016

FIX THREE WIRES TO TRANSISTOR, SOLDER AND PUT SLEEVE	1.26	0.0041
FIX THREE WIRES ON CAPACITOR, TWO RED WIRES TO ANOTHER POINT, SOLDER AND CUT TIPS	0.77	0.0137
UNTIE THREE ORANGE BUNCHES	0.62	0.0092
HARNESS THE ABOVE BUNCH	1.40	0.0131
TIE UP TUNER BUNCH	0.25	0.0016
PICK UP YOKE, FIX TWO WIRES AND SOLDER	0.69	0.0033
PICK UP BOARD ON EHT AND FIX TC TEN PIN CONNECTOR	0.53	0.0148
BEND WIRES IN 'U' SHAPE AND FIX TO TEN PIN CONNECTOR	0.57	0.0070
SOLDER ON TEN PIN CONNECTOR AT FIVE PLACES	0.43	0.0158
FIX 10 WIRES ON ONE TEN PIN CONNECTOR AND FIX 7 WIRES ON ANOTHER TEN PIN CONNECTOR	1.26	0.0054
SOLDER AT ALL SEVENTEEN PLACES	0.98	0.0376
CUT TIPS	0.34	0.0011
BEND THE WIRES IN PROPER POSITION	0.49	0.0037
REMOVE THE BOARD ON EHT	0.15	0.0019
FIX THE CAPACITOR	0.27	0.0025
PICK UP BLUE WIRE BUNCH AND FIX TWO WIRES OUT OF THEM	0.45	0.0119
PREPARE THE CAPACITOR	0.88	0.0136
FIX THE CAPACITOR ON THE POTENTIOMETER	0.24	0.0009
TAKE YELLOW BUNCH AND FIX THREE WIRES	0.41	0.0039
SOLDER THE ABOVE SIX POINTS	0.92	0.0310
CUT THE TIPS	0.28	0.0026
PICK UP AERIAL STRIP PLATE AND FIX TWO WIRES	0.41	0.0061
FIX TWO MORE WIRES ON AERIAL STRIP	0.30	0.0133
FIX ANOTHER TWC WIRES ON AERIAL STRIP	0.22	0.0064
SOLDER THE ABOVE SIX POINTS	0.50	0.0110
HARNESS POTENTIOMETER WIRES AND FIX TWO WIRES ON POTENTIOMETER PLATE	2.41	0.1610
STRIP AND TIN TWO WIRES IN THE BUNCH	0.83	0.0287
FIX ONE BLACK WIRE AND ONE SHIELD WIRE TO POTENTIOMETER	0.78	0.0202
FIX SIX WIRES CN POTENTIOMETER PLATE	1.05	0.0154
CHECK AND FIX TWO WIRES ON 10K OHM RESISTOR	0.57	0.0095
CHECK AND FIX TWO WIRES ON 5K CHM RESISTOR	0.36	0.0044
SOLDER THE ABOVE FOUR POINTS	1.16	0.1296
CUT EXTRA LENGTHS AFTER SOLDERING	0.41	0.0091

TABLE B-2

DATA ON OPERATOR PERFORMANCE

POOL	NO. OF OPERATORS	RATING OF LABOUR POOL
	1	85.00
	1	90.00
	6	95.00
	2	100.00
	1	110.00

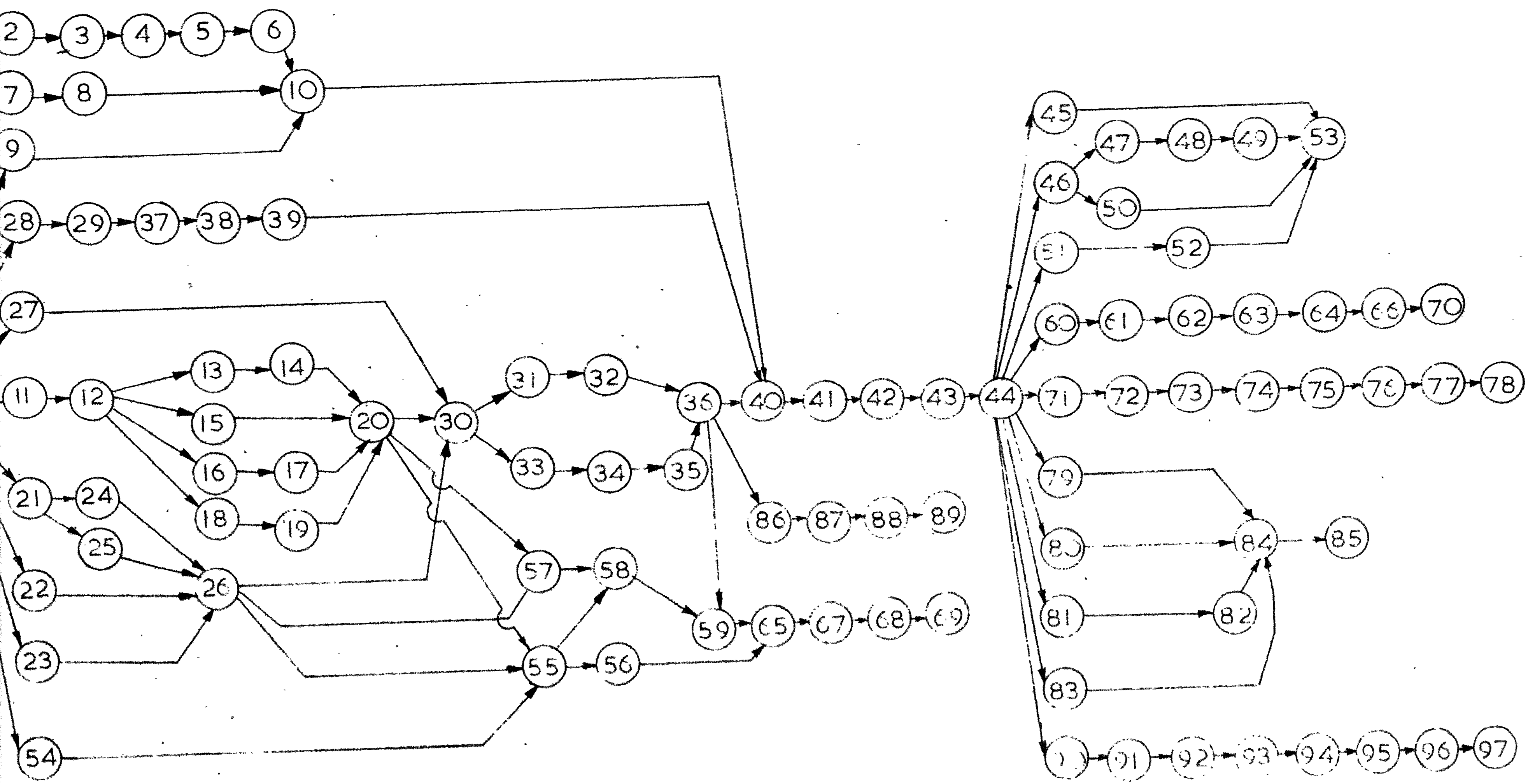

FIG. B1 PRECEDENCE GRAPH - TV FINAL ASSEMBLY

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APENDIX-C
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ERATOR FINAL ASSEMBLY PROBLEM - DATA

TABLE C-1

DATA ON WORK ELEMENTS

ELEMENT DESCRIPTION	MEAN TIME (SEC)	VARIANCE (SEC)**2
APPLY BITUMINOUS SEALING COMPOUND TO BACK FLANGES OF THE CABINET LEFT HAND SIDE	14.1	11.6
APPLY BITUM)NOUS SEALING COMPOUND TO BACK FLANGES OF THE CABINET BOTTOM	13.1	9.4
APPLY BITUM)NOUS SEALING COMPOUND TO BACK FLANGES OF THE CABINET RIGHT HAND SIDE	12.6	6.64
APPLY BITUM)NOUS SEALING COMPOUND TO BACK FLANGES OF THE CABINET TOP	15.4	23.84
APPLY BITUM)NOUS SEALING COMPOUND TO BOTTOM FLANGES OF THE CABINET RIG+T HAND SIDE	43.6	46.44
APPLY BITUM)NOUS SEALING COMPOUND TO BOTTOM FLANGES OF THE CABINET LEFT HAND SIDE	4 .1	29.2
APPLY BITUM)NOUS SEALING COMPOUND TO BOTTOM FLANGES OF THE CABINET FRONT	1 .3	24.41
PLACE TOP HINGE ASSEMBLY COMPONENTS IN POSITION	15.5	17.65
FIX TAPPING PLATE FOR TOP HINGE	24.4	20.24
FIX SCREWS OF TOP HINGE	44.0	16.24
FIX TAPPING PLATE FOR LOCK ASSEMBLY	111.3	6.21
FIX LOCK HINGE SCREWS BY HAND	55.3	55.62
FIX LOCK HINGE SCREWS BY SCREW-DRIVER	26.9	22.29
PLACE BOTTOM HINGE COMPONENTS IN POSITION	23.7	53.21
FIX ONE BOLT OF BOTTOM HINGE BY HAND	18.6	30.24
FIX ANOTHER BOLT OF BOTTOM HINGE BY HAND	20.7	39.21
TIGHTEN BOTTOM HINGE BOLTS BY WRENCH	23.6	20.04
PLACE RUBBER GARMENTS FOR FIXING LINER	31.2	6.64

›ICK UP FIBRE GLASS(BACK AND TOP PIECES)	11•6	6•44
ALIGN AND FIX BOTTOM FIBRE GLASS PIECE	67•4	30•81
ALIGN AND FIX TOP FIBRE GLASS PIECE	32•1	30•28
›ICK UP FIBRE GLASS(TWO SIDE PIECES)	18•6	24•04
ALIGN AND FIX LHS FIBRE GLASS PIECE	39•4	7•41
ALIGN AND FIX RHS FIBRE GLASS PIECE	40•8	7•44
PLACE FIBRE GLASS PACKING IN CORNERS	4 •8	8•04
GET THE LINER	12.8	3.36
PULL-OUT THE CONNECTING WIRES	24•0	9•40
POSITION AND FIX THE LINER	53•4	43•81
PLACE WASHER AND NUTS TO FIX LINER	58•8	30•04
FIX THE LINER TO THE CABINET	54•0	26•80
FILL GLASS FIBRE BETWEEN LINER AND CABINET	88•2	33•24
GET THE FOUR BREAKER STRIPU	2 •2	4•64
FIX LHS AND RHS BREAKER STRIPS	38•8	13•24
FIX TOP AND BOTTOM BREAKER STRIPS	2 •8	21•04
TIGHTEN THERMOSTAT SCREW (TOP)	3 •5	19•04
TIGHTEN THERMOSTAT SCREW (+OTTOM)	28•6	16•84
ENLARGE HOLE ON CABINET TO FIX CLIP	8•9	3•09
PLACE GAMMET RUBBER BUSH	38•6	13•64
GET THE WIRE ASSEMBLY	18•6	5•24
CONNECT WIRE ASSEMBLY TO LINER	4 •9	11•4
INSEE		
INSERT PVC SLEEVE ON THREE WAY CONNECTORS	1 •7	3•61
PLACE PANNEL COVER	15.4	17.44
FIX FOUR PANNEL COVER SCREWS	6 •5	39•25
INSERT CLIP WITH BUSH	2 •1	30•8
FIX WIRE ASSEMBLY TO CABINET	14•8	11•16
TWIST THE WIRES	8.6	2.44
CUT FIBRE GLASS PIECE TO INSERT EVAPORATOR	28•0	33•60
REMOVE AND PLACE FIBRE GLASS PIECE ON CONVEYOR	3•9	1•69
CUT CENTRE PIECE OF FIBRE GLASS	18•5	14•85
GET THE COOLING SYSTEM ASSEMBLY	31•6	12•64
REMOVE THE CLIPS FROM THE SYSTEM	12•6	5•64
INSERT THE EVAPORATOR INTO CABINET	15•9	17•49
FIX FOUR EVAPORATOR SCREWS BY HAND	51•8	14•96
TIGHTEN TWO SCREWS BY SCREW DRIVER	30•8	9•16
TIGHTEN TWO SCREWS BY SCREW DRIVER	31•4	4•24
FIX PLAIN-CLIP SCREWS TO EVAPORATOR BY HAND	13•5	3•65
PLACE ZHE CAPILLARY IN POSIZION	29•4	8•84
PLACE THE TAPPING PLATE	25•4	12•44
FIX -LAIN CLIP SCREWS TO EVAPORATOR BY SCREW DRIVER	15.3	1.01

TIE THREAD AROUND COVER OF APPERTURE ASSEMBLY	32.4	9.07
PLACE BULB HOLDER IN POSITION	29.4	10.04
FIX BULB HOLDER	24.8	9.3
ALIGN AND FIX BACK PANNEL ASSEMBLY	53.7	21.82
PLACE APPERTURE ASSEMBLY IN POSITION	14.4	1.64
PLACE POLYTHENE COVER AND GLASSWOOL PACKING	7.2	6.36
FIX SCREW1 OF PANEL COVER	20.1	10.49
FIX SCREW2 OF PANEL COVER	1 .9	13.6
FIX SCREW3 OF PANEL COVER	13.3	3.21
FIX SCREW4 OF PANEL COVER	14.0	13.00
FIX SCREW5 OF PANEL COVER	11.7	5.81
FIX SCREW6 OF PANEL COVER	17.6	17.24
FIX SCREW7 OF PANEL COVER	15.8	7.76
FIX SCREW8 OF PANEL COVER		
FIX SCREW9 OF PANEL COVER	13.1	4.49
FIX SCREW10 OF PANEL COVER	13.2	7.36
FIX SCREW11 OF PANEL COVER	10.6	2.44
FIX SCREW12 OF PANEL COVER	15.0	4.69
ALIGN SUCTION TUBE	43.1	17.89
PLACE GOMOUET BUSH	5.3	4.21
FURTHER ALIGN SUCTION TUBE	5.9	2.49
BEND SUCTION TUBE HOLDING CLIP	5.9	2.09
PLACE NUTS IN POSITION	27.4	16.04
BEND SUCTION TUBE CLIP	30.6	2.61
FURTHER ALIGN SUCTION TUBE	62.2	24.29
FIX FOUR NUTS OF COMPRESSOR	68.0	28.69
ALIGN THE CONDENSOR	27.0	11.40
BEND CONDENSOR CLIPS	30.9	16.49
FIX UPPER GUARD OF THE CONDENSOR	65.6	33.92
FIX LOWER GUARD OF THE CONDENSOR	77.6	11.84
FIX FIRST CORNER BREAKER STRIP	13.9	3.6
FIX SECOND CORNER BREAKER OTRIP	13.6	1.44
FIX THIRDD CORNER BREAKER OTRIP	13.5	8.05
FIX FOURTH CORNER BREAKER STRIP	12.1	1.8
LIFT THE DOOR TO POSITION	75.2	26.14
FIX TOP HINGE ASSEMBLY OF THE DOOR	88.2	32.64
FIX BOTTOM HINGE ASSEMBLY OF THE DOOR	99.6	27.76

TABLE C-2

DATA OPERATOR PERFORMANCE

5	3	100.00
6	4	105.00
7	1	110.00
2	2	85.00
3	4	90.00
4	8	95.00

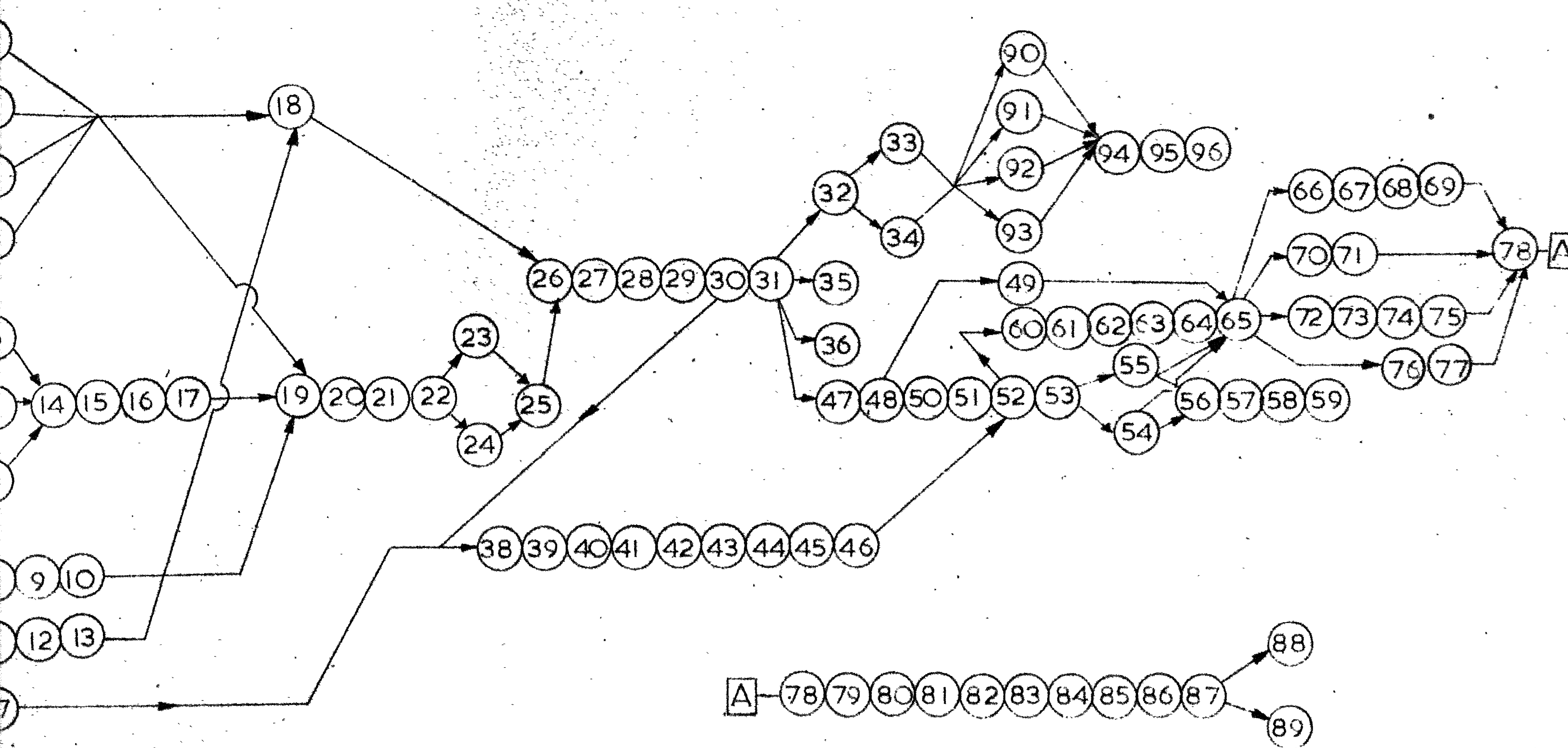

FIG. C-1 PRECEDENCE GRAPH - REFREGIRATION FINAL ASSEMBLY

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APENDIX -D

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TRUCK ASSEMBLY PROBLEM

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TABLE D-1

DATA ON WORK ELEMENTS

MEAN SEC	VARIANCE SEC*2	FOLLOWING OPERATIONS					
.60	.9604	2	0	0	0	0	
.15	4.2354	3	0	0	0	0	
.35	.0486	4	0	0	0	0	
.15	10.6178	5	6	7	8	9	10
.90	.1046	39	0	0	0	0	
.25	1.3260	39	0	0	0	0	
.69	.0468	83	0	0	0	0	
.52	2.4850	71	0	0	0	0	
.19	.0194	11	12	0	0	0	
.35	2.1179	71	0	0	0	0	
.81	.0021	22	23	24	25	0	
.50	24.5025	26	0	0	0	0	
.77	.0015	27	0		0	0	
.89	.0027	28	0	0	0	0	
.51	.0031	29	0	0	0	0	
.64	.0726	3[illegible]	0	0	0	0	
.05	.2945	9[illegible]	0	0	0	0	
.60	.1835	111	0	0	0	0	

1.25	.0014	31	83	0	0	0		
34.29	6.7914	32	33	0	0	0		
.43	.0007	69	70	0	0	0		
34.30	.7953	34	0	0	0	0		
19.60	.1859	82	0	0	0	0		
.29	.0014	35	0	0	0	0		
.27	.0023	36	0	0	0	0		
.15	.0004	37	0	0	0	0		
1.21	.0263	38	0	0	0	0		
17.15	2.1753	39	0	0	0	0		
21.27	17.0275	41	0	0	0	0		
14.70	.0138	111	0	0	0	0		
40.37	12.0535	42	0	0	0	0		
.68	.0071	43	0	0	0	0		
.62	.0089	44	91	0	0	0		
.42	.0025	45	91	0	0	0		
3.64	.0076	46	91	0	0	0		
49.98	33.9488	40	0	0	0	0		
14.70	5.3945	111	0	0	0	0		
29.63	34.4186	69	70	0	0	0		
56.89	9.4349	47	0	0	0	0		
.68	.0118	48	49	91	0	0		
.18	.000	50	0	0	0	0		
.10	.0002	51	0	0	0	0		
.81	.0098	52	0	0	0	0		
52.00	23.8925	54	55	56	57	58	59	60
.39	.0025	53	0	0	0	0		
.67	.000	91	0	0	0	0		
.27	.0002	111	0	0	0	0		
.15	.0004	111	0	0	0	0		
1.21	.0165	111	0	0	0	0		
.58	.0129	111	0	0	0	0		
17.15	10.6178	69	70	0	0	0		
1.25	.0008	61	62	63	0	0		
40.10	29.7418	63	64	0	0	0		
14.70	5.1248	65	91	0	0	0		
14.70	.1245	66	91	0	0	0		
23.03	.6131	67	91	0	0	0		
19.60	.4441	68	91	0	0	0		
22.05	8.9928	69	70	0	0	0		
40.18	7.0325	71	0	0	0	0		
27.44	13.1195	111	0	0	0	0		
29.99	.1295	72	0	0	0	0		
7.35	.7021	111	0	0	0	0		
7.35	.4773	111	0	0	0	0		
7.35	.0625	111	0	0	0	0		
7.35	.2498	111	0	0	0	0		
5.45	.0058	77	78	0	0	0		
33.86	3.3432	73	0	0	0	0		
32.34	19.3445	91	0	0	0	0		

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APENDIX-E

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LIST OF VARIABLES USED IN CALBPROP I AND II

MEAN OF STATION DISTRIBUTION
PRODUCT OF NUMBER OF WORK ELEMENTS IN THE FIT LIST
ISPR
WEIGHT OF WORK ELEMENT IN THE FIT LIST
SUM OF WEIGHTS OF WORK ELEMENTS IN THE FIT LIST
ABSOLUTE TIME
CYCLE TIME
AVERAGE NUMBER OF WORK ELEMENTS AVAILABLE FOR A PARTICULAR POSITION IN THE SEQUENCE OF WORK ELEMENTS
AVERAGE NUMBER OF WORK ELEMENTS AVAILABLE AT ALL TIMES
SUB-TOTAL OF RELATIVE WEIGHTS OF WORK ELEMENTS
AVERAGE OF THE MAX NUMBER OF WORK ELEMENTS AVAILABLE FOR ALL POSITION IN THE SEQUENCE
AVERAGE OF THE MIN NUMBER OF WORK ELEMENTS AVAILABLE FOR ALL POSITION IN THE SEQUENCE
WORK ELEMENT TIME VARIANCE
POINTS ON RANDOM NUMBER SCALE SEPARATING WORK ELEMENTS
RANDOM NUMBER BETWEEN 0 AND 1
NUMBER OF A COMPLETE SEQUENCE
B
TOTAL NUMBER OF WORK ELEMENTS WHICH FOLLOW A WORK ELEMENT
INDEX NUMBER
ORDINAL NUMBER OF NEXT WORK ELEMENT IN THE SEQUENCE
ORDINAL NUMBER OF A POSITION OF
ORDINAL NUMBER OF A POSITION IN THE SEQUENCE OF A WORK ELEMENT AT A STATION
NUMBER OF WORK ELEMENT WHICH FOLLOWS A WORK ELEMENT
COUNT OF NUMBER OF SEQUENCE TRIED AT A STATION
NUMBER OF STATION IN A COMPLETE ASSIGNMENT(BEST)
NUMBER OF WORK ELEMENTS ASSIGNED TO A POSITION IN THE SEQUENCE
STATION NUMBER OF AN ASSIGNED WORK ELEMENT BY SEQUENCE POSITION
NUMBER OF WORK STATION
STATION NUMBER OF AN ASSIGNED WORK ELEMENT BY SEQUENCE POSITION
NUMBER OF UNASSIGNED WORK ELEMENTS WHICH PRECEDE A WORK ELEMENT IMMEDIATELY
NUMBER OF SEQUENCE REQUIRING A GIVEN NUMBER OF STATION
LIMIT OF NUMBER OF SEQUENCES TO TRY AT A STATION
INDEX NUMBER

STATION NUMBER RELATED TO THE LAST PRINTED WORK ELEMENT
INDEX NUMBER
NUMBER OF WORK ELEMENT IN THE AVAILABILITY LIST
INDEX NUMBER
NUMBER OF WORK ELEMENTS WHICH PRECEDES A WORK ELEMENT
TOTAL OF NUMBER OF WORK ELEMENTS AVAILABLE FOR A POSITION
IN SEQUENCE FOR ALL SEQUENCES
INDEX NUMBER
NUMBER OF SEQUENCES TO BE ATTEMPTED
ORDINAL NUMBER OF THE BEST ATTEMPTED SEQUENCE
INDEX NUMBER
SEQUENCE LIMIT FOR A STATION
NUMBER OF SEQUENCE TRIED AT A STATION
NUMBER OF SEQUENCE AS GOOD AS THE BEST AT A STATION
ORDINAL NUMBER OF THE PRINTED SEQUENCE AT A STATION
LIST OF WORK ELEMENTS AVAILABLE FOR ASSIGNMENT
LIST OF WORK ELEMENTS WHICH SATISFY FIT CONSTRAINTS
LIST OF WORK ELEMENTS AVAILABLE FOR ASSIGNMENT
POSITION IN THE SEQUENCE
LIST OF WORK ELEMENTS AVAILABLE AFTER THE BEST SEQUENCE FOR
A STATION HAS BEEN FOUND
NUMBER OF WORK ELEMENTS WHICH IMMEDIATELY FOLLOW A WORK ELEMENT
NUMBER OF ASSIGNMENTS WHEN LOADING STATIONS MAXIMALLY
TOTAL MINIMUM NUMBER OF WORK ELEMENTS AVAILABLE FOR ALLPOSITIONS
IN THE SEQUENCE
NUMBER OF LEVELS OF ALL FOLLOWING WORK ELEMENTS
THE PREVIOUS POSITION IN A SEQUENCE OF WORK ELEMENTS
NUMBER OF LABOUR POOLS
NUMBER OF SEQUENCES AS GOOD AS THE BEST AT A STATION
AN INDICATION WHEN ONE WORK ELEMENT IS PRECEDED BY ANOTHER
NUMBER OF PREVIOUS STATION OR A WORK ELEMENT NUMBER
IN THE MASTER STATION LIST
WORK ELEMENT NUMBER IN THE LIST TO BE PRINTED
NUMBER
MAXIMUM NUMBER OF WORK ELEMENTS AVAILABLE FOR A POSITION
FO* ALL SEQUENCES
MIN NUMBER OF WORK ELEMENTS AVAILABLE FOR A POSITION FOR ALL SEQU
NUMBER OF WORK ELEMENTS AT A LOADED STATION TO BE PRINTED
TEMPORARY STORAGE OF NOLP
NUMBER OF WORK ELEMENTS WHICH IMMEDIATELY PRECEDE A WORK ELEMENT
NUMBER OF WORK ELEMENTS IN THE AVAILABILITY LIST
NUMBER OF WORK ELEMENTS IN THE AVAILABILITY LIST
NUMBER OF WORK ELEMENTS WHICH IMMEDIATELY FOLLOW A WORK ELEMENT
NUMBER OF WORK ELEMENTS IN THE FIRST AVAILABILITY LIST
NUMBER OF WORK ELEMENTS IN THE FIT LIST
NUMBER OF OPERATORS IN LABOUR POOL
NUMBER OF WORKERS ON THE LINE
NUMBER OF SELECTED WORK ELEMENTS
NUMBER OF FOLLOWING WORK ELEMENT
NUMBER OF WORK ELEMENTS WHICH IMMEDIATELY FOLLOW A TASK